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USN manpower determination decision making: a case study using imprint pro to validate the LCS core crew manning solution

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THESIS

USN MANPOWER DETERMINATION DECISION MAKING: A CASE STUDY USING IMPRINT PRO TO VALIDATE THE LCS CORE CREW MANNING SOLUTION

by

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Kelly M. Leszczynski

December 2014

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Using IMPRINT Pro Forces software, three different LCS core crew sizes were modeled to assess how each was able to handle day-to-day operations, maintenance, and emergencies during a (notional) operational underway. As crew sizes are reduced, individual performance becomes increasingly important. Multiple watch schedules were modeled using the FAST software tool, which uses the SAFTE model to predict individual cognitive effectiveness levels using a simulated work and sleep schedules.

Using the IMPRINT Pro Forces modeling tool, this study found measurable and significant differences in performance among the three core crew sizes as assessed by ANOVA and Tukey tests. The FAST results showed conclusively that individual performance is significantly affected by the watch rotation a sailor stands. Although this thesis focused on the crew of the LCS, the modeling approach and analytical process can be expanded and applied to a wide range of ships and departments.

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LIST OF ACRONYMS AND ABBREVIATIONS

ANOVA	analysis of variance
AMD	activity manpower document
ARL	Army Research Laboratory
ASW	anti-submarine warfare
BAC	blood alcohol concentration
CMC	command master chief
CNA	Center of Naval Analysis
CO	commanding officer
CSG	carrier strike group
DoD	Department of Defense
ESG	expeditionary strike group
FAST	Fatigue Avoidance Scheduling Tool
HRED	Human Research and Engineering Directorate
HSD	honestly significant difference
HSI	human systems integration
IMPRINT	Improved Performance Research Integration Tool
MANPRINT	manpower and personnel integration
MCM	mine counter-measures
MP	mission package
MPT	manpower, personnel, and training
MTBF	mean time between failures
NAVMAC	Naval Manpower Analysis Center
NPS	Naval Postgraduate School
NREM	non-rapid eye movement
NSWC	Naval Surface Warfare Center
NSWW	Navy standard work week
ONR	Office of Naval Research
PPBES	planning, programming, budgeting, and execution system
REM	rapid eye movement
ROC/POE	required operational capability/projected operational environment

RSN	random seed number
SAFTE	sleep, activity, fatigue, and task effectiveness
SCN	suprachiasmatic nucleus
SMART	Ship Manpower Requirements and Analysis Tool
SMD	ship manpower document
SUW	surface warfare
SWO	surface warfare officer
TCM	Total Crew Model
U.S.	United States
USN	United States Navy
XO	executive officer

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I. INTRODUCTION

Over a decade ago, the United States Navy (USN) launched the Surface Combatant Program. Three new classes of ships were developed: the DD(X) Destroyer (re-designated the DDG-1000), the CG(X) Cruiser, and the Littoral Combat Ship (LCS). Their development signaled a departure from legacy ships in that each aimed to substitute advanced technology and automation for manpower—an extension of a decade-long, experimental policy called optimal manning. This policy prioritized re-organizing work, cross-training personnel, and substituting automation for sailors in order to reduce crew sizes. To date, however, these acquisitions have fallen short of the vision that was cast for them as evidenced by the reduction of the DDG-1000 class to only three ships, the termination of the CG(X), and reductions of LCS combatants from 52 to just 24 (O'Rourke, 2014). Bloated development costs and downsized budgets are largely to blame for the termination of the CG(X) program and the drastic reductions in the DD(X) and LCS. Since these ships were designed to operate with crew sizes far smaller than legacy ships, these reductions could also be indicative of a failed manpower strategy in addition to budget battles.

The U.S. Navy has struggled with shipboard manning levels over the last decade. Optimal manning was conceived to control costs; its practice, however, has put undue stress on sailors who are overworked and ships that fail to pass inspections. The failure of this strategy came about, for the most part, because the workload reductions promised by the new technology did not occur. As billets were reduced to comply with optimal manning policies, the workload of those remaining personnel increased—sometimes to the breaking point. Failed periodic readiness inspections and decreased maintenance capability over the past decade caused Navy leadership to re-evaluate optimal manning as a policy, as well as the practice of minimal manning. In 2011, Undersecretary of the Navy Robert Work said, "We have concluded [optimal manning] went too far… The material condition of the fleet we believe suffered because of it" (as cited in Fuentes, 2011).

In order to ensure the full service life of its ships, the Navy has reversed course, sending thousands of sailors to fill “optimal manning” billets previously cut from cruisers, destroyers, and dock landing ships (Fuentes, 2011). It is critical to accurately determine the manpower required to operate a ship. Overstating enlisted ship manpower requirements diverts limited resources away from other important expenditures. Understating manpower requirements, on the other hand, can negatively impact ship operations, maintenance, crew performance, morale, readiness, and ultimately, mission accomplishment.

A. CASE STUDY BACKGROUND

> Our Navy starts with the Fleet. Everything we do must keep the Fleet ready and make it even better. We must accurately define and continuously validate our requirements, then move aggressively to fully fund those requirements. In doing so, we will ensure the Fleet remains ready to fight and win.
>
> —Admiral Vern Clark, CNO 2002 (Ham, 2002)

Manpower can easily become the largest cost of any developed system; thus, the desire to reduce manpower and its costs will always be present (Alper & Koopman, 2006). In contrast, ensuring correct manning levels for proper ship operation and safety is vitally important and requires constant evaluation of the Navy’s fleet manpower determination processes and policies. This thesis will serve as a case study to assess the accuracy and feasibility of using government-developed, human performance software to assist in ship manpower determination. A software program called the Improved Performance Research Integration Tool (IMPRINT) Pro has been under development by the U.S. Army Human Research and Development Command for the past decade (U.S. Army Research Laboratory, 2010).

An IMPRINT model was built of the crew of the LCS to understand the effects of different ship crew sizes. In addition, the Fatigue Avoidance Scheduling Tool (FAST), an instantiation of the Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE) model, was applied to aid in understanding how human cognitive effectiveness fluctuates as a function of work schedule and sleep at the individual level (Institutes for Behavior

Resources, 2012). When crew size decreases, workload and crew fatigue almost always increase, leading to a decline in combat readiness and other negative consequences.

The Navy designed the LCS to operate with a crew severely reduced in comparison to other ships of similar size (e.g., light frigates or coast guard cutters). An LCS operates with a *core crew* of only 40, not including the commanding officer (CO), executive officer (XO), and command master chief (CMC). To operate with a core crew of this size, the LCS relies heavily on automation and supplements its core crew with additional sailors from whatever mission module is onboard. The mission module crewmembers also help operate weapon systems and aircraft, in addition to performing tasks specific to that mission. Compared to the 200+ sailors operating a Navy frigate, or the 300+ crewmembers operating cruisers and destroyers (O'Rourke, 2012), the size of an LCS core crew seems exceptionally small. Congressional reports have questioned the sufficiency of this core crew size stating that, in addition to creating a fragile operating environment, crew fatigue sets in by the third day underway (Carpaccio, 2013). Previous Naval Postgraduate School theses have also suggested that an LCS core crew of 40 is neither sufficient nor sustainable (Douangaphaivong, 2004; Williams-Robinson, 2007).

IMPRINT Pro and FAST are both products developed by the Department of Defense (DOD), and are designed to assist in conducting human performance analyses. IMPRINT Pro consists of four autonomous modules: the Mission module, the Equipment module, the Warfighter module, and the Forces module. Each module is purposely designed to offer specific data outputs to inform different decisions. IMPRINT Pro Forces module has been designed to estimate manpower requirements at the unit level. More specifically, using stochastic simulation, it can be used to predict the manpower needed to perform the routine work done by a force unit. The U.S. Navy has used the IMPRINT Mission, Equipment and Warfighter modules with success; however, the IMPRINT Forces module has never before been used for Fleet manpower determination. FAST is a quick, easy, and portable software tool that uses a person's 72-hour sleep history to calculate the work schedule and watch rotation effects on an individual's predicted alertness and cognitive effectiveness. The FAST software program has been used operationally by the U.S. Air Force, the Naval Safety Center, the Federal Aviation

Administration, and the Federal Railroad Administration. It is the official model selected by the Department of Defense to predict individual cognitive effectiveness. Used together, IMPRINT Pro Forces and FAST have the potential to evaluate the effect of manning levels for various naval units, including the LCS. Ultimately, these software programs may be beneficial in the Navy's fleet manpower determination process.

B. CASE STUDY OVERVIEW

This thesis is an LCS manpower case study developed in three distinct efforts: IMPRINT Pro Forces model simulations, FAST model predictions, and a survey administered to the current crewmembers of the USS *Independence* (LCS 2) to assess their perception of the adequacy of current manning concepts.

Three different LCS force units representing three different LCS core crew sizes were created using IMPRINT Pro Forces software. The IMPRINT Pro Forces module gives performance data for a collective unit; it does not, however, show the effectiveness of an individual throughout a period of time. As crew sizes are reduced, individual performance becomes increasingly important since there is no spare crew capacity to fall back upon in the case of a crewmember's incapacitation.

FAST uses the SAFTE model to predict cognitive effectiveness. FAST model predictions for this case study involved modeling notional watch schedules using the FAST software tool, which uses the SAFTE model to predict individual cognitive effectiveness levels using a simulated work and sleep schedule. The FAST results for this case study give the reader a general idea of a sailor's predicted effectiveness level while executing daily tasks under certain work and rest schedules.

For the third portion of this thesis, a survey was developed specifically for this case study and administered to the crewmembers of LCS 2 to elicit their feedback on current watch rotations, sufficiency of allotted manpower, and daily operational requirements. This survey was constructed, in part, to see how well the output and results of the IMPRINT Pro Forces and FAST models reflect actual LCS crewmember perceptions of the current manpower condition.

C. LCS BACKGROUND

Slightly smaller than a frigate, the LCS is a multi-functional platform, designed to replace USN guided missile frigates (FFGs), mine countermeasure ships (MCMs), and patrol crafts (PCs). There are two variants of the LCS platform, as shown in Figure 1. The first platform design that was built, the USS *Freedom* (LCS 1), is a monohull design, developed and built by Lockheed Martin at Marinette Marine in Marinette, Wisconsin. The second platform design, the USS *Independence* (LCS 2), is a trimaran design, developed and built by General Dynamics at the Austal USA Shipyard in Mobile, Alabama. As stated in OPNAVINST 3501.352 (a rough draft of the required operational capability/projected operational environment (ROC/POE) for LCS), the LCS is designed to operate offensively in a multi-threat environment concentrated in near-shore waters independently or as an integral member of a carrier strike group (CSG), expeditionary strike group (ESG), or surface action group. The key feature of LCS is its reconfigurable mission packages that allow the ship to refocus war fighting capability between different mission areas, including mine counter-measures (MCM), surface warfare (SUW), or anti-submarine warfare (ASW).

Figure 1. Lockheed LCS design (top) and General Dynamics LCS design (bottom) (from O'Rourke, 2012)

1. LCS Manning

Originally, the LCS was designed to operate with a total core crew of 40, not including the CO, XO, and CMC. This core crew of 40 was comprised of eight officers and 32 enlisted sailors. The LCS currently employs a *Blue-Gold* manning concept, where two core crews conduct a swap midway through deployment, allowing the ship to remain on station. In order for an LCS to operate with minimal manning and rotating crews, sailors are required to have multiple skills and perform multiple functions. Every sailor fills a billet that has extensive and well-defined training requirements for maintenance duties, watch standing, and other tasks.

The LCS capabilities are based on interchangeable, "plug-and-fight" mission packages (MPs) focused on ASW, MCM, and SUW. The different LCS mission packages come with their own operators and maintainers in addition to the LCS core crew. Each MP typically contains 15 to 20 sailors depending on the package, and an air detachment crew of 20 to 25. The core crew is designed to operate the ship independently, since an MP crew and/or air detachment are not always aboard the ship.

2. Current LCS Manning

LCS 2 operates with an intended core crew size of 40, not including CO, XO, and CMC. LCS 1 originally operated with the intended core crew size of 40; however, it received a core crew "plus up" of nine enlisted sailors and one officer before its first operational deployment, bringing its core crew total to 50 sailors, not including the CO, XO, and CMC. These numbers were based on the LCS activity manpower document (AMD) and data cards collected by the Center for Naval Analysis (CNA) from the USS *Freedom's* (LCS 1) first deployment on March 1, 2013 to December 31, 2013. CDR Daniel Degner, COMLCSRON ONE N5/N8, provided these data cards to NPS. According to the CNA data cards for LCS 1 Blue Crew, the following nine enlisted sailors were added to each department: four to engineering, two to operations, two to combat systems, and one to supply to total an enlisted core crew size of 40 and a total LCS core crew size of 50. (For unknown reasons, LCS 1 Blue Crew had data on only 31 enlisted core crew before the "plus up" of nine enlisted, versus Gold Crew's 32 enlisted core crew.)

D. CASE STUDY ORGANIZATION

For the IMPRINT modeling effort of this thesis, three different models were made using the different LCS enlisted core crew sizes of 31, 40, and 48 (corresponding to a total core crew of 40, 50, and 60 when officers are included) to determine which core crew size showed the best response to planned activities and unplanned events during a notional underway period. The initial IMPRINT Pro Forces model was based upon Blue Crew's enlisted core crew of 31, since the CNA data for the Blue Crew was more complete. The first model reflects the LCS 1 enlisted core crew manning level without the nine enlisted sailor "plus up," as well as the initial enlisted manpower estimates for the LCS. (The enlisted core crew size of 31 is meant to simulate an LCS total core crew of 40.) The second model was built using 40 enlisted core crew sailors to reflect the current LCS 1 enlisted manning level with the "plus up" of nine enlisted core crew sailors (The LCS enlisted core crew size of 40 is meant to simulate an LCS total core crew of 50.) The third model was built as a notional enlisted core crew of 48 to test IMPRINT Pro's ability to measure differences in multiple crew sizes. (The LCS enlisted core crew size of 48 is meant to simulate an LCS total core crew of 60, assuming a total of 12 officers.) For the notional enlisted core crew of 48, two enlisted sailors were added to each of the following LCS departments: engineering, operations, combat systems, and supply.

For the second part of the thesis, FAST was used to analyze current watch schedules found on LCS 1 and LCS 2. Because the results of the IMPRINT Pro Forces module address the total crew and do not reflect the effectiveness of an individual throughout a period of time, FAST was used to estimate individual effectiveness levels. We reviewed the individual activity data from each of the three IMPRINT models and reviewed output data from Random Seed Number 3. We then reviewed the individual data from the two sailors with the most and least sleep from each crew. We then modeled their 21-day schedules in FAST.

Part three of this thesis contains the results of a survey administered to the Gold Crew aboard the *Independence* (LCS 2) in January of 2014. This baseline survey was developed to collect data on crewmember attitudes about LCS during an actual underway period. The survey was developed specifically for this case study and was administered to LCS 2 crewmembers to solicit personal opinions about current watch rotations, the relative workload of departments and positions, and the amount of sleep that current watch rotations allow.

E. CASE STUDY OBJECTIVES

The first objective of this case study was to assess the applicability of using human performance software to validate manpower requirements and to determine what utility IMPRINT Pro Forces offers in predicting manpower levels. When used correctly, human performance software can inform ship manpower estimates and help prevent the execution difficulties that often occur after manpower requirements are determined for new acquisitions and existing platforms. Together, the three sections of this thesis are meant to assess the use of human performance modeling tools as additional resources that decision makers can use to determine ship manpower requirements. The second objective of this case study is to assess the capability of IMPRINT Pro Forces to determine manpower requirements for an LCS force unit by first determining if the enlisted core crews of 31, 40, and 48 provide adequate manning to successfully complete all planned activities and unplanned events during a notional 21-day underway period. Differences between each core crew model are analyzed and then tested for statistical significance using an analysis of variance (ANOVA) test to detect significant differences ($p < .05$) exist among the three models. The Tukey Honestly Significant Difference (HSD) test is used to show where those differences exist. The third objective of this case study is to use FAST to analyze different watch schedules found on LCS 1 and LCS 2. Because the results of the IMPRINT Pro Forces module address the total crew and do not reflect the effectiveness of an individual throughout a period of time, FAST is also used to illustrate the effectiveness levels of individual sailors dependent upon work start and end times, and the watch rotations and sleep times simulated by IMPRINT Pro Forces. The LCS 2 survey collected data on crewmembers' perceptions of the watch rotations, the underway workload of departments and positions, and the amount of sleep the current watch rotations allow underway in order to see if the IMPRINT Pro Forces and FAST model outputs are correctly reflected in LCS crewmember responses.

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II. LITERATURE REVIEW

A. FLEET MANPOWER REQUIREMENTS DETERMINATION

1. Process

The primary facility for determining fleet manpower requirements is the Naval Manpower Analysis Center (NAVMAC) in Millington, Tennessee. NAVMAC used a multistep process in manpower requirements determinations. The first step identifies "zero-based" manpower requirements, those requirements determined without regard to funding constraints, by gathering a variety of inputs from the fleet. Once NAVMAC determines these requirements, they become the wartime requirement. A requirement becomes a billet once funding and end-strength are allocated during the planning, programming, budgeting, and execution system (PPBES) process, which takes into account fiscal constraints and will not be discussed further.

The OPNAVINST 1000.16K, *Manual of Navy Total Force Manpower Policies and Procedures*, is the overarching naval instruction that provides guidance on manpower policy and procedures. This document explains the processes for ship manpower determination, and specifies that personnel levels must be adequate to perform the Navy's work and carry out specific missions. However, as policy, the DoD requires that the Navy use the "least number of people possible" to accomplish its missions (Moore et al., 2002, p. 12).

There are three main documents that result from the Fleet manpower requirements determination process. The required operational capabilities (ROC) and the projected operational environment (POE) document establishes ship missions and capabilities and provides a measurable level of crew workload for a specific class of ships, such as an LCS. Minimum manpower requirement levels are based on these workloads. To determine the manpower requirements (at the most basic level), NAVMAC uses an approved Navy standard workweek (NSWW) to calculate the minimum number of personnel required to accomplish average, daily workload and all the missions and tasks of the ROC/POE. These numbers are then reflected in the class ship manpower document

(SMD). Once the manpower requirements are identified in the SMD and funded by the PPBES process, they become billets and are identified in activity AMDs by unit identification code (UIC).

2. Navy Standard Workweek

The Navy Standard Workweek (NSWW) gives baseline timetables for personnel work, watch, and duty requirements for operational afloat and ashore commands. These workweek standards can be found in OPNAVINST 1000.16K. NSWWs are one of the key elements used in manpower requirement calculations, and are intended as tools for managing personnel and establishing working hours. Commands, however, are under no obligation to adhere to them.

LCS manpower requirements are determined by NAVMAC using the afloat (wartime) NSWW, which assumes steaming in wartime/deployed cruising readiness under a three-section watch. There are 168 hours in a week. The NSWW further divides this time into 81 hours of available time and 87 hours of non-available time. Of the 81 hours of available time each week, the time of a sailor is allocated to 56 hours of watch, 14 hours of work, and 11 hours of training/service diversion, equating to 70 hours per week available (56 hrs of watch + 14 hrs of work) for productive work. The 87 hours of non-available time consists of 56 hours of sleep (8 hours per 24 hour period), 14 hours for eating (messing), and 17 hours of free time (which includes 3 hours of extra free time on Sundays). Figure 2 displays the afloat NSWW. These times are only guidelines to model sustained workforce schedules and do not reflect personnel endurance limits. IMPRINT may be helpful in addressing inadequacies in the current NSWW models.

Afloat (Wartime) - Military Personnel		
Ship Standard Workweek		81.00 hrs
Productive Workweek (NOTE 1)		**70.00 hrs**
Analysis of Duty Hours		
Total hours available weekly		168.00
Less Non-Available Time:		
Sleep	(56.00)	
Messing	(14.00)	
Personal needs	(14.00)	(87.00)
Sunday (free time)	(3.00)	
Scheduled On Duty Hours Per Week		81.00
Less:		
Training (NOTE 2)	(7.00)	
Service diversion (NOTE 3)	(4.00)	(11.00)
Total Hours Available for Productive Work (NOTE 1)		**70.00**

Figure 2. Afloat (wartime) NSWW (from DON, 2007). For watch standers, 56 hours is allocated to watch stations (8 hours x 7 days) (14 hours available for work in addition to 56 hours watch standing = 70 hours)

The NSWW is one of the primary metrics used by NAVMAC to determine fleet manpower. NAVMAC translates workload estimates into manpower requirements (billets) using the navy manpower requirements system (NMRS). At the most basic level, this NMRS uses an interactive optimization program that bases crewmember productive work on the NSWW (Moore et al., 2002). To ensure that naval ships are manned at sufficient levels, it is important that the NSWW and the assumptions used to translate workload into manpower requirements remain applicable. Efforts designed to reduce manpower requirements in technologically advanced ships have led to crew sizes far smaller than those seen in the past. The smaller the crew the less they are able to absorb extra work. Thus, ensuring the accuracy of the NSWW is even more important.

Various allowances are used by NAVMAC to ensure the NMRS output is an accurate calculation of workforce requirements. For example, the Productivity Allowance is a "percentage applied to basic productive work requirements to reflect delays from fatigue, environmental effects, personal needs, and unavoidable interruptions, increasing time required for work to be accomplished"; the Make Ready/Put Away Allowance refers to “steps required in obtaining and returning necessary instruction manuals, tools, and materials and transit to and from the work area (GAO, 2010, p. 5).”

The Navy’s optimal manning initiative was in place from 2001 to 2009 and resulted in a 20% decrease in enlisted requirements (GAO, 2010). To achieve this reduction in personnel, certain standards used to determine workforce requirements were altered. To decrease workforce requirements, NAVMAC increased the NSWW from 67 to 70 hours productive work hours and substantially decreased allowances. For example, the Make Ready/Put Away Allowance was reduced from 30% to 15% and the Productivity Allowance was reduced from 20% to a floating range between 2% and 8% (GAO, 2010). In short, constraints to NMRS were reduced in order to reduce ship crew sizes. However, this GAO report and another similar report from the Naval Audit Service (2005), “found that these changes were not based on verifiable analysis or data” and were not the result of the type of analysis required by OPNAVINST 1000.16K (GAO, 2010, p. 18). Surface manpower levels were changed without verifiable, justifiable data, and the negative outcomes associated with these changes were alarming. A report entitled *The Fleet Review Panel of Surface Force Readiness* (2010) documented many of these negative outcomes. The three-hour increase to productive work hours alone reduced shipboard manning by up to 4% and optimal manning cut 4,052 sailors from surface ships, but workload reductions did not decrease along with manpower (Balisle, 2010). Remaining Sailors could not adequately handle the workload and their morale, health, and performance declined along with the material readiness of the fleet (Balisle, 2010). According to the 2007 article, Avoiding A Second Hollow Force: The Case for Including Crew Endurance Factors in the Afloat Staffing Policies of the U.S. Navy:

> The Navy should expand its investment in human systems integration, focusing on human performance as a critical component of total system performance. Thereby, we will ensure that future platforms have fully integrated the human strengths and weaknesses into the system design. Such actions will lead to the right answer, resulting in optimal use of scarce human resources. The Navy needs a better understanding of the consequences of these manning decisions if we are to deliver the level of combat capability required to protect our national interests abroad. (Miller & Firehammer, 2007, p. 95)

The material readiness of surface ships and the health and performance of sailors, are dependent on adequate manning levels, therefore the Navy must ensure that these manpower levels are accurately determined.

B. HUMAN PERFORMANCE FACTORS

Systems are comprised of both human and technological subsystems (Miller, Crowson & Narkevicius, 2003; Shattuck & Miller, 2007). When manpower levels are reduced to a minimum level, it is critically important to understand the consequences this action will have on the human part of the system—and it is therefore even more important to understand the strengths and limitations of the humans operating and maintaining these systems.

Human beings are not machines. However, like machines, they do require maintenance and “fuel” replenishment. Humans have basic requirements to sustain health and life; these include water, food and sleep. Absence of any of these three basic requirements for a prolonged period of time will result in death. If these basic requirements are insufficient over a shorter period of time, the humans will no longer function at expected levels. When manpower levels are reduced so that there is little to no redundancy, there is risk to both personnel and mission. It is essential to understand human performance factors (and the limitations thereof) and to implement policies that protect personnel from debilitating effects of illness, injury and fatigue.

1. Sleep

Sleep is a natural bodily function; its complete purpose, however, still remains somewhat of a biological mystery. As such, the complete link between sleep and health is not yet fully understood. Although the benefits are not yet fully understood, the negative consequences of partial or total sleep deprivation are well documented. Lack of sleep contributes to poor performance and poor health. Job errors and accidents, as well as many health-related illnesses such as obesity, diabetes, and immune system dysfunction are linked to a lack of sufficient sleep (Lambert, 2005). Human performance and productivity degradation results from sleep deprivation. Scientific studies have demonstrated that sustained wakefulness in the range of 17–24 hours produces a psychomotor deficit equivalent to the performance of an individual with a blood alcohol concentration (BAC) of 0.05% to 0.10% (Dawson & Reid, 1997).

When the human body is asleep, many important restorative functions occur. Sleep is essential to the replenishment of energy and brain processes. Multiple studies found significant impairments in brain functions such as memory, vigilance, cognitive speed, spatial orientation, and motor control in individuals subjected to total sleep deprivation lasting longer than a day or partial sleep deprivation over a few days (Belenky et al., 1994; Horne & Pettitt, 1985; Krueger, 1989; Lorenzo et al., 1995; Rogers et al., 2003). It is sleep deprivation studies in rats, however, that provides some of the most compelling evidence supporting the importance of sleep. The normal life span of a rat is 2–3 years, but "rats deprived of Rapid Eye Movement (REM) sleep survive an average of only five months. Rats deprived of all sleep survive only about three weeks" (NHLBI, 2013, para. 3.8). These experiments with animal models expose the clear link between sleep and health; as do rats and all other mammals, humans require sleep to live.

Sleep is an active process. There are five stages of sleep and the body will undergo each stage multiple times during a normal 8-hour sleep period. Figure 3 displays the sequence humans undergo during a typical 8-hour sleep period. Sleep is divided into two basic categories: non-rapid eye movement (NREM) sleep and rapid eye movement (REM) sleep. Sleep begins in stage one and progresses to stage four, after which stages three and two are repeated and the body then enters the last stage (REM). Body temperature drops and heart rate slows in stage two and the body enters deep sleep in stage three. The brain is extremely active throughout each stage and brain activity will change with each sleep stage. In REM sleep, brain activity is highest. Typically, after REM is complete the body falls back into stage two sleep and the process repeats until waking.

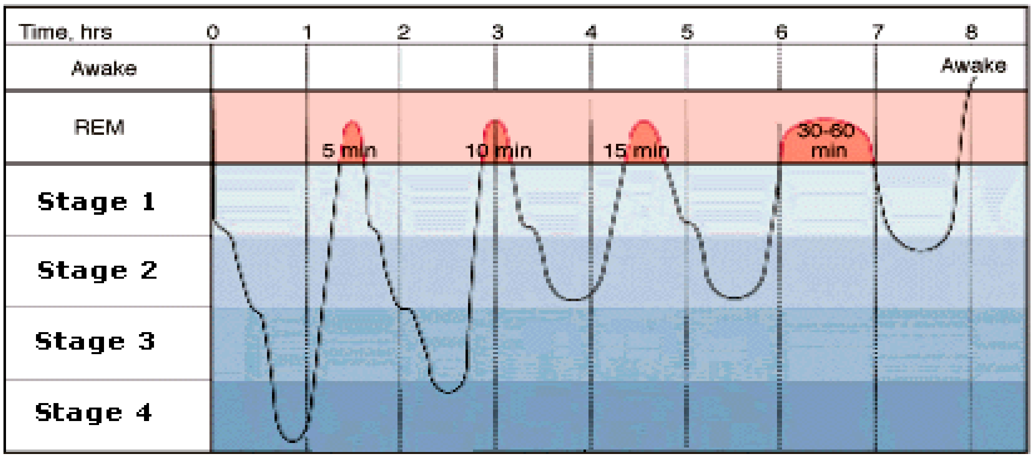


Figure 3. Sleep stages over a customary 8-hour sleep period (from Atranik, 2013a)

The quantity of sleep that a person requires varies throughout life. Figure 4 shows how sleep patterns change from fragmented sleep in infants, to sleeping through the night with short afternoon naps in the toddler years. Young adults need significantly more sleep than adults; studies indicate young adults are shown to need 8.5 to 9.25 hours of sleep nightly (Miller & Shattuck, 2005), and approximately .5 to 1.25 more hours per night than the average 25-year-old (Carskadon et al., 1995; Wolfson & Carskadon, 1998, 2003). According to the Defense Manpower Data Center Active Duty Personnel Master File, in 2011 the U.S. Navy employed 128,210 active-duty enlisted under the age of 25 (DUSD(C&PP), 2012). Approximately 49.3%of all enlisted active-duty personnel are under the age of 25 (DUSD(C&PP), 2012). As these scientific studies show, the amount of rest that a sailor receives is extremely important to health and performance and varies significantly with age. When calculating the sleep deficit of members of the military, the distributions of age is an important factor to consider since these young junior enlisted and junior officers may fall into the adolescent/young adult sleep category and may actually require more sleep than their adult (over 25 years old) counterparts.

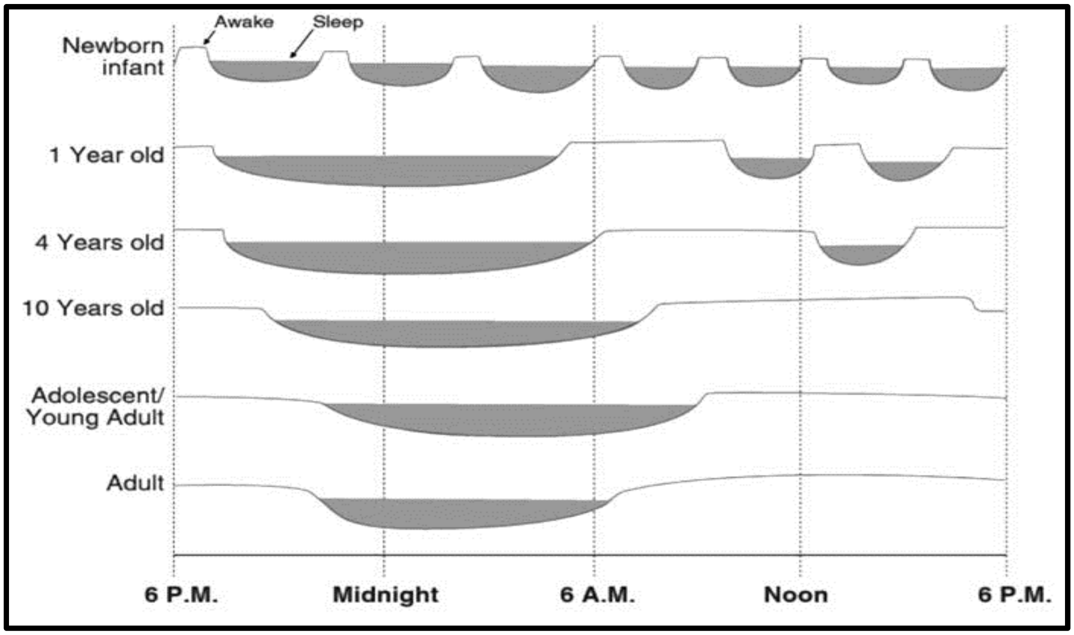


Figure 4. Lifespan sleep patterns (from Miller & Firehammer, 2007)

Navy sailors are allotted 8 hours of rest per day, as specified by the NSWW. Many studies, however, have determined sailors are getting significantly less than 8 hours of sleep when at sea (Haynes, 2007; Green, 2009; Mason, 2009). According to self-reported sleep data gathered over a three-month period by CNA, the core crew aboard LCS 1 averaged just 5.7 ± 1.2 hours of sleep per night during their first deployment; yet the crews considered this normal. CNA analysts also recognized that this average sleep amount dropped by .5-hour while underway; this finding was statistically significant at the 95% confidence level.

Busy schedules and fragmented watch rotations are not the only challenges sailors face in their quest for sufficient rest. The ship environment has many factors that can affect a sailor's ability to obtain restful sleep. Noise, smells, vibration, light, temperature changes, uncomfortable racks, and changes in sleeping surroundings all negatively impact sleep duration and quality (NHLBI, 2013, para. 4.0). Given the nature of military schedules and requirements, quality sleep is not always possible for many sailors.

2. Circadian Rhythms

The body experiences a natural, sleep-wake cycle consisting of approximately 8 hours of sleep and 16 hours of wakefulness under normal conditions every 24 to 25 hours. The onset of sleep is controlled by a combination of two physiological and neurological functions in the body: sleep homeostasis and circadian rhythm.

The homeostatic process is entirely physiological. A person will naturally become more tired the longer they are awake regardless of external conditions due to a sleep-inducing chemical called adenosine. From the moment a person wakes, the body is creating adenosine and the more it builds the more difficult it becomes to stay awake. Eventually, the body will no longer be able to resist this build up and will succumb to sleep. An internal "clock," along with external factors, drives an individual's circadian rhythm. Circadian rhythms can be described as the physical, mental, and behavioral changes the body undergoes under a 24- to 25-hour period. A properly functioning circadian rhythm is extremely important to physical and mental health. Research shows that irregular circadian rhythms are associated with obesity, diabetes, depression, bipolar disorder, and seasonal affective disorder (Boden, Chen, & Urbain, 1996; Foy, 2010; Germain & Kupfer 2008; Rosenthal et al., 1984; Wittke-Thompson et al., 2008). The body's natural circadian rhythm endeavors to keep a person awake as long as there is daylight, and because the circadian process is highly evolved, it is highly resistant to change.

The hypothalamus of the brain contains an area called the suprachiasmatic nucleus (SCN). The SCN is responsible for "setting" the body's circadian clock based on internal and external factors, and then mediates hormonal and temperature changes designed to induce sleep in the body based on these internal or endogenous cues. External factors or exogenous cues, such as light, meals, exercise, and the 24-hour day followed by society all help entrain the body's natural circadian rhythm. The largest influences are the daylight/darkness cycle and a person's work/social schedule (National Sleep Foundation, 2006). Internally, even without these external cues, the body will naturally follow a 24- to 25-hour innate clock (Horne, 1988).

Figure 5 shows a typical circadian rhythm experienced by an adult human over a sleep/wake cycle of 24–25 hours. Early in the morning, the body's metabolism increases, the body naturally awakens, and the SCN ceases melatonin secretion. The body experiences a series of peaks and lulls in alertness throughout the afternoon until evening. As darkness sets in, the optic nerves sense the lack of light and send this information to the SCN causing it to again secret melatonin. The body sleeps, and the process begins anew.

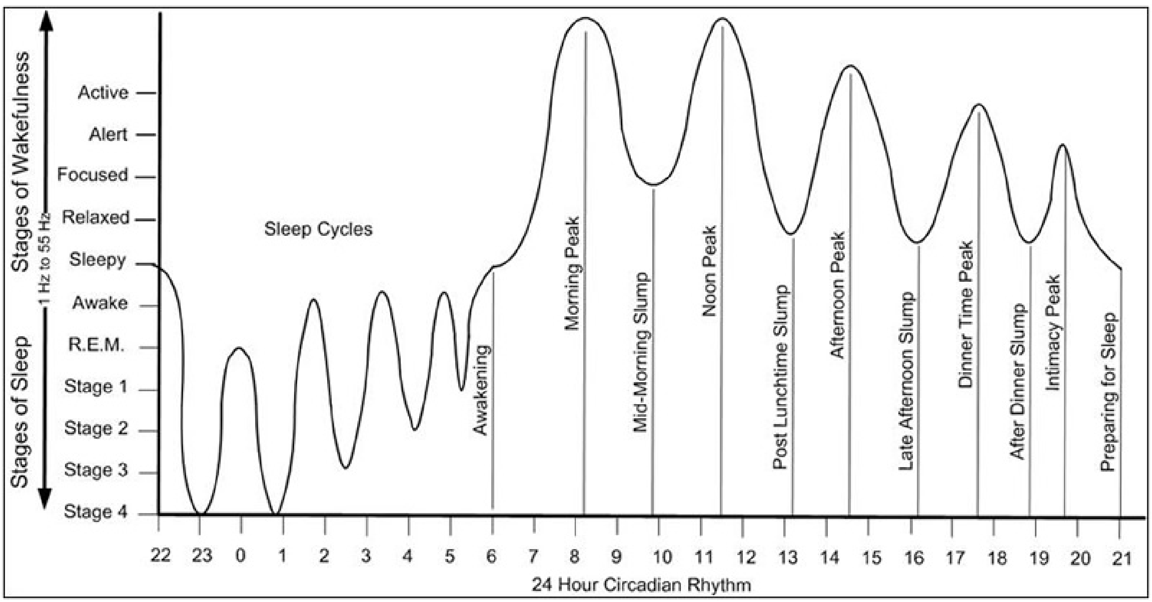


Figure 5. The body's 24- to 25-hour circadian rhythm (from Antranik, 2013b)

The natural circadian process for humans is to stay awake during daylight, and to sleep with the onset of darkness. If the circadian rhythm is out of synchronization, sleep disruption can occur and health-related issues may also arise because the human body simply does not handle disruptions to this cycle well. A perfect example of this is when a body adjusts to crossing multiple time zones. Desynchronosis ("jetlag") occurs when the normal light/dark schedule that a person has grown accustomed to changes. Shift workers, individuals working other than a 9 to 5 schedule, show similarities to persons affected by jetlag (Waterhouse, 1999).

3. Shiftwork

Shiftwork is found in any organization that must operate 24 hours a day, 7 days a week, and exists extensively in both the civilian sector and the military community. The term "shiftwork" refers to two or more groups of people working a range of hours that enables an operation to extend beyond the normal operating hours of human capacity (Harrington, 2001). Shiftwork has been employed by a number of industries for decades because it allows for continuous coverage of necessary activities and one in five civilians are now subjected to this type of work schedule (Monk, 2012). Nurses, firefighters, police officers, airline pilots and flight attendants, military members, etc., are all considered shift workers. The Navy surface warfare community has one of the greatest exposures to shiftwork. Afloat, the community employs day and night watch rotations in order to conduct continuous operations. Despite the organizational benefits of shiftwork, advancement in sleep-related knowledge continues to shed new light on the practice, and the harmful effects it has on human health.

Shiftwork disrupts a worker's circadian rhythm, builds an unhealthy sleep deficit, and increases fatigue, leading to workplace inefficiency (Harrington, 2001). A person exposed to shiftwork experiences changes to their sleeping, eating, and working habits that then changes their body temperature peak times, respiratory rate, and hormone production (Harrington, 2001). When a person is rotated from day to night and vice versa on a daily or weekly basis, that person suffers degradation in health, performance, and effectiveness. Night shift workers display the most concerning effects; a medical diagnosis of shift work disorder, or SWD is identified by the cluster of symptoms they commonly experience.

The natural human tendency is to sleep at night because of natural cues for wakefulness during the day (e.g., light, social schedules, work schedules, circadian rhythms). For night shift workers, however, the quality and quantity of sleep obtained during daylight hours is often not sufficient to return the body to an acceptable performance state. Studies show that night shift workers receive on average 1–4 hours less sleep than day workers (Akerstedt, 1990). Furthermore, night shiftwork exposure has been associated with poor sleep in retired seniors 65 years old and older, compared to retired day workers from the same age group (Monk, 2012). High operational tempos and deployment schedules virtually guarantee that sailors will be exposed to the harmful health effects of shiftwork and night shiftwork.

4. Fatigue

The Oxford English Dictionary (2014) defines fatigue as "extreme tiredness." Fatigue resulting from physical exertion and mental fatigue are the two most familiar types of fatigue. Mental fatigue is when one feels sleepy and is unable to focus or concentrate and is used to describe a more long-term or chronic state of tiredness. The limitations of the human body make fatigue extremely common, especially in taxing jobs like those of today's sailors.

Regardless of how many hours, days, weeks, or months they must work, military members are required to perform until the mission is done. Studies show, however, that excessive fatigue can negatively affect cognitive performance and lead to reduced reaction times and decreased vigilance (Krueger, 1989). Persistent fatigue can negatively affect personnel and team performance, mission accomplishment, safety, and morale. An environment of sustained work, fatigue, and sleep loss can create harmful physiological and psychological effects that negatively impact individual performance (Krueger, 1989). Impaired logical reasoning, vigilance, attention, mental tasks, reaction times, and situational awareness all can be negative effects of fatigue (Dinges et al., 1997; Belenky et al., 2003; Krueger, 1989). Studies show human cognitive performance is closely linked to quality and quantity of sleep (Mullaney, Kripke, & Fleck, 1989); by far the biggest contributor to fatigue is lack of sleep.

Chronic sleep restriction directly affects an individual's cognitive abilities, and the longer the sleep debt the longer an individual will take to recover full cognitive ability. Figure 6 shows a depiction of a study that was done to assess daytime performance changes as a result of chronic sleep restriction or augmentation, and subsequent recovery sleep. Referred to as the Walter Reed Restricted Sleep Study, three groups of individuals were restricted to either 3, 5, 7, or 9 hours of sleep for 1 week, followed by three days recovery of 8 hours rest per 24 hours. The graph shows the performance of the individuals as measured by a psychomotor vigilance task (PVT) assessment. The PVT measures simple reaction time to a visual stimulus. The 3-hour group's performance increases rapidly after 1 night of recovery. But, the 3-hour group only reaches a level consistent with the 5- and 7-hour groups despite 2 more nights of recovery. The 5- and 7-hour groups are able to recover slightly with 1 night of recovery; they never reach the performance displayed by the 9-hour group, however. The 9-hour group's performance remains consistently high. These results show conclusively that restricted sleep limits brain operational capacity and that the problem persists even after normal sleep is restored (Belenky et al., 2003). As this study shows, a human being is not restored to a level of full alertness even with subsequent sleep when their fatigue is the result of a sleep deprivation pattern.

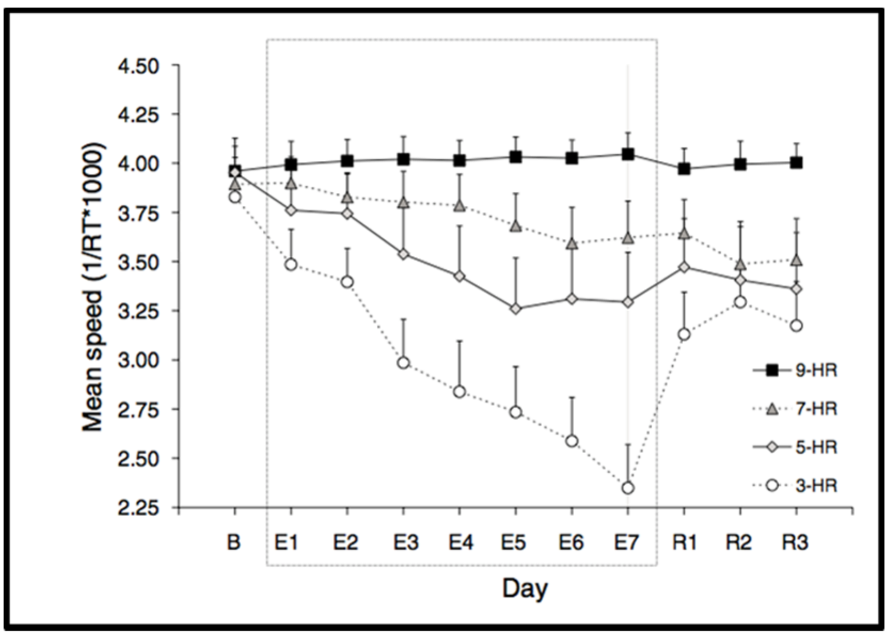


Figure 6. PVT speed test results of 3-, 5-, 7-, and 9-hour groups (from Belenky et al., 2003)

C. WATCH-STANDING SCHEDULES

Watch standing is a very important duty performed by Navy sailors. Maintaining a professional, vigilant watch rotation is vital to keeping the ship safe and in good working order. Every naval ship employs watch schedules that operate continuously

24 hours a day, 7 days a week. A sailor's watch duties can range from monitoring equipment to carrying a weapon during force protection watches. There are many different watch-section combinations a ship can employ, but the most common watch schedules are two-section, three-section, and four-section.

Two-section watch schedules are employed when there is a shortage of qualified personnel to stand watch, or there are just simply not enough personnel to allow a watch schedule with more sections. A two-section watch rotation, also referred to as a "port and starboard," can be set up as a fixed rotation as shown in Table 1, or "dogged" rotation as shown in Table 2. On a fixed rotation, sailors stand the same watch every day, as shown in Table 1. On the two-section "dogged" rotation shown in Table 2, sailors stand a different watch by shifting their watch rotation forward. For example, if they stand the 0600–1200 section watch today, tomorrow they will stand the 1200–1800 section watch. On the two-section "dogged" watch, the evening sections last only 3 hours.

2	0600-1200	1	1	1	1
	1200-1800	2	2	2	2
	1800-0000	1	1	1	1
	0000-0600	2	2	2	2

Table 1. Two-section watch

2	0600-1200	2	1	2	1
	1200-1800	1	2	1	2
	1800-2100	2	1	2	1
	2100-0000	1	2	1	2
	0000-0600	2	1	2	1

Table 2. Two-section watch "dogged"

Perhaps the most typical three-section watch rotation used in the U.S. Navy is referred to as "five and dimes," as shown in Table 3. Sailors are on watch for 5 hours and off for 10 hours. Unlike the straight two-section watch, the three-section rotation equates to a 30-hour day, versus a 24-hour day in the two-section watch.

3	0700-1200	1	3	2
	1200-1700	2	1	3
	1700-2200	3	2	1
	2200-0200	1	3	2
	0200-0700	2	1	3

Table 3. Three-section watch

On the four-section watch schedule, as shown in Table 4, sailors stand watch for 5 hours and are then off for 15 hours. This watch rotation rotates and sailors stand a different section watch each day. The four-section equates with a 20-hour day.

4	0700-1200	1	2	3	4
	1200-1700	2	3	4	1
	1700-2200	3	4	1	2
	2200-0200	4	1	2	3
	0200-0700	1	2	3	4

Table 4. Four-section watch

Not having enough qualified personnel to stand watch is an issue that ship crews encounter on a regular basis. If only a small number of personal are qualified to stand watch, the number of watch "sections" a watch schedule can have is limited. The Navy does not regulate how many watch sections a ship is required to have, but rather regulates that sailors maintain a professional and vigilant watch. OPNAVINST 1000.16K states, "To reduce the total number of hours personnel are required to be on board for work and duty, commanding officers shall maintain the maximum feasible number of duty sections" (Appendix C, C-1). Ship departments, however, employ the watch rotation that best fits the number of qualified people available, or commanding officers will simply choose one section over another.

D. IMPRINT PRO FORCES

IMPRINT is a stochastic simulation software program used to support manpower and personnel integration within military weapons systems. It was originally used for Army human systems integration (HSI) and Army manpower and personnel integration

(MANPRINT) efforts. Developed by Alion Science and Technology and the Army Research Laboratory (ARL) Human Research and Engineering Directorate (HRED), IMPRINT is a dynamic, stochastic, and discrete event network and modeling tool that uses the Windows operating system. IMPRINT software was originally designed for Army use although the U.S. Navy has contributed support for further development of IMPRINT. There was a version of IMPRINT designed specifically for the U.S. Air Force. The newly expanded IMPRINT Pro, however, is now used by all branches of the military.

IMPRINT Pro has the capability to assist in identifying manpower constraints in a system by assessing manpower requirements or the limitations of available manpower early in the systems acquisition process. IMPRINT Pro evaluates the manpower and personnel needed to effectively operate and maintain a system using task analysis, workload modeling, and embedded personnel characteristics; it does this through the use of four modules: Mission, Equipment, Warfighter, and Forces (IMPRINT, 2013b). Each IMPRINT Pro module features a unique graphical user interface and is a stand-alone package that allows the user to model discrete, dynamic, and/or stochastic events as appropriate for specific mission, equipment, or manpower analysis (IMPRINT, 2013c). When used together or individually, these modules provide estimations of manpower, personnel, and training (MPT) requirements and constraints for a range of systems.

The Army has used IMPRINT Pro software to determine operator workload and manning levels, and analysts have successfully used the IMPRINT Pro Mission, Warfighter, and Forces modules to conduct human performance analyses. These modules have potential use in Navy fleet manpower determination processes. Each IMPRINT Pro module produces its own data outputs in the form of Excel spreadsheets, charts, and graphs that allow analysts to evaluate system performance and personnel availability an capability. These data outputs are then used to create a more accurate prediction of the manpower estimates for successful system operation and maintenance according to established standards. The IMPRINT Pro Forces module provides information outputs to accurately estimate the effects of manpower changes on planned and unplanned work before system implementation or may be used to refine manpower estimates after the system is in place.

The IMPRINT Pro Forces module estimates the feasibility of mission accomplishment with the manpower assigned to a unit. It is able to predict how a unit will perform with additions or reductions of personnel and how changing manning impacts mission capability and crew performance. Specifically, the Forces module assesses a unit's response to planned activities and unplanned events based on different manpower levels. (Planned events are events that the unit expects to complete on a daily basis whereas unplanned events are either emergencies or events that interrupt daily planned activities and must be resolved.)

The Forces module represents the actual workings of a unit and can be divided into two categories: activities and jobs. Activities are tasks performed by the force unit while jobs are the people who perform and accomplish those activities. Once a model is built and run, Forces uses a stochastic simulation engine to simulate the baseline utilization of all jobs in various activities according to the schedules defined over a designated period of time (IMPRINT, 2013a). The module also simulates in parallel the defined unplanned events that are designed to disrupt these ongoing activities (IMPRINT, 2013). The data spreadsheets generated from this simulation forecast the performance and effectiveness of a unit by showing the unit's capability to address events over a length of time specified (IMPRINT, 2013a). The Forces module can thus determine how well a unit addressed planned activities and unplanned events encountered over an established period of time by showing whether that event failed, how long before the activity or event failed, and why the activity or event failed. By analyzing these outputs, manpower discrepancies can be identified and quantified by the number of failures that occur when the model is changed to different levels of manpower or different skill sets.

E. FAST AND THE SAFTE MODEL

FAST is a software program that uses the SAFTE model to predict and analyze an individual's cognitive effectiveness based on their sleep and work schedule over a specified period of time. The DoD-developed SAFTE model has been scrutinized closely under scientific review (Hursh, Balkin, Miller, & Eddy, 2004); the DoD considers SAFTE to be their model of choice since it has less error compared to other developed models. The SAFTE model is based on 20 years of sleep and circadian rhythm research, and shows accurate and validated predictions of worker performance as a function of actual or simulated sleep data, work schedules, rest periods, and travel periods. The SAFTE model can accurately predict cognitive performance by using information from an individual's actual or hypothetical sleep/wake cycle and work schedule (Hursh et al., 2004). This prediction is then displayed through the user-friendly FAST program.

The SAFTE model is the foundation of the FAST software and it is what gives FAST such accurate outputs. Figure 7 shows a typical FAST display output for an individual over a period of time. The Windows-based FAST graphically displays cognitive performance predictions during an individual's schedule. FAST is used specifically to find weaknesses and vulnerabilities in current schedules and allows schedules to be changed easily or modified in order to identify optimized schedules, given operational constraints. FAST uses work schedules and sleep data and factors in the circadian process, sleep propensity, and sleep fragmentation to display changes in an individual's cognitive performance and provide an estimation of future performance.

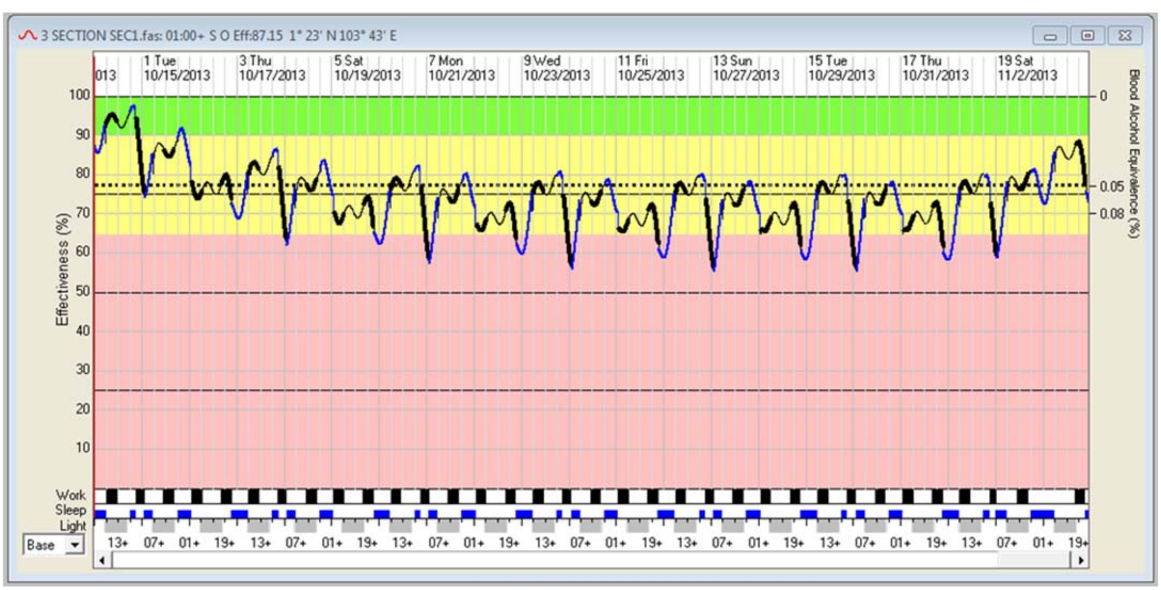


Figure 7. FAST graphical results of an individual on a three-section watch rotation ("five and dimes")

The DoD considers FAST a critical aid in operator scheduling. The U.S. Air Force and U.S. Army have successfully used the FAST software tool operationally. The Air Force uses FAST to determine aviation schedules that ensure crews are sufficiently rested for the entire mission; thus creating an optimal schedule that can offer a safer crew environment. The Navy also has areas that warrant the use of FAST to include the Naval Safety Center that mandates that all naval mishap investigations apply FAST to the mishap findings. If used correctly, FAST can help assess alertness during mission-critical tasks, reduce fatigue-related errors, and help to ensure the health of military members.

F. OTHER HUMAN PERFORMANCE MODELING TOOLS

Using human performance software programs such as IMPRINT Pro and FAST in the fleet manpower determination process is a way to obtain more accurate manpower requirements estimations and determine better watch schedules for crews. The Ship Manpower Requirements and Analysis Tool (SMART), the Total Crew Model (TCM), and the IMPRINT Pro Mission module are all examples of human performance software tools that were considered as potential alternatives to using the IMPRINT Pro Forces module to evaluate the LCS manning levels for this case study.

SMART is a manpower prediction tool and, like IMPRINT Pro, was developed by Alion Science and Technology. SMART was developed for the Office of Naval Research (ONR) and the Naval Surface Warfare Center (NSWC) to help analyze manpower requirements and automation of equipment prior to new technology implementation. SMART and IMPRINT Pro were both built to be used early in the acquisition process so that costly mistakes could be avoided. SMART is designed to analyze automation and manpower together and is typically used before automated systems are integrated. For the current thesis, SMART was not used because the system (in this case, LCS) was already in operation and this case study dealt primarily with manpower levels.

Also developed by Alion Science and Technology, TCM concentrates on the performance of the unit as a whole and results are based heavily on the NSWW for naval applications. While TCM analyzes time limits and has a daily schedule interrupted by unplanned events, its analysis on a less refined scale as that in IMPRINT Pro Forces. The

IMPRINT Pro Forces module focuses on time attributes to determine manpower requirements based solely on response time and how long planned activities and unplanned events take to complete. TCM, however, answers whether the crew can successfully complete all missions within a certain amount of fatigue. TCM is labor-intensive to populate the data sets and analyze; in addition, it has not been updated to run on more recent computer operating systems. Consequently, TCM is no longer used and IMPRINT Forces was designed to be its replacement. IMPRINT Pro Forces has elements of TCM incorporated into its design, allowing Forces to offer many of the same capabilities as TCM, but in a more user-friendly software program.

The IMPRINT Pro Mission module concentrates on a smaller portion of a unit, such as a department or division. The results of the Mission module answer whether the workload of that crew is too high. The goal of the Mission module is to determine manpower performance along with system performance. Since the Mission module did not have the capability to model or evaluate the performance of an entire ship crew collectively, the IMPRINT Pro Mission module was not used in this thesis. IMPRINT Pro Forces was selected because it is more flexible and capable of handling a more diverse set of manpower analyses, such as comparing ship crew sizes. Before this thesis, the IMPRINT Pro Forces program had not been utilized for ship manpower determination, the purpose of this thesis and the case study effort.

III. METHODOLOGY

A. METHODOLOGY OVERVIEW

This thesis is an LCS manpower case study encompassing three related but distinctly different efforts. These efforts include (1) the IMPRINT Pro Forces module, (2) the FAST/SAFTE model, and (3) a survey administered to current crewmembers aboard LCS 2. The objective of this case study is to assess the use of human performance software to validate manpower requirements. More specifically, it assesses the applicability of IMPRINT Pro Forces in determining manning levels early in program development. Theoretically, human performance software should provide more accurate estimates of ship manpower and help prevent some of the inevitable consequences that often occur when manpower requirements for new acquisitions and existing platforms are determined.

Part one of the methodology describes how each of the three IMPRINT Pro Forces models was built for a notional LCS operational underway period. Part two of the methodology describes how notional watch schedules were modeled using FAST, which uses the SAFTE model to predict individual effectiveness levels utilizing work and sleep data. While actual sleep data were not collected from LCS crews for this analysis, the authors used FAST to show how an individual's cognitive effectiveness varies depending on the 72-hour the sleep history. Part three discusses the development, administration and analysis of a survey administered to the crew of the USS INDEPENDENCE (LCS 2) to elicit feedback on current watch rotations, allotted manpower, and daily operational requirements in order to determine whether the IMPRINT Pro Forces and FAST model outputs reflect the crewmembers' perceptions of their current manning levels.

B. IMPRINT PRO FORCES MODULE METHODS

1. IMPRINT Model Overview

The IMPRINT Pro Forces Module is designed specifically to determine a unit's manpower requirements and may be useful in determining a surface ship's manpower requirement. It can reveal inadequacies in a unit's assigned personnel by revealing how many planned activities and unplanned events fail due to lack of required personnel for the planned activity or unplanned event.

Three different IMPRINT models were built using three different LCS enlisted core crew sizes (i.e., 31, 40, and 48, which correspond to total core crew of 40, 50 and 60) to determine which crew size showed the fewest failures of planned activities and unplanned events during a typical underway period. The planned activities and unplanned events were scripted by the authors and then refined using input from a veteran LCS Operations Officer, LCDR Matthew L. Muehlbauer, USN. The first model (enlisted core crew of 31) was built to reflect both the current USS *Independence* (LCS 2) configuration and the initial enlisted manning estimates for LCS. The second model (enlisted core crew of 40) reflects the current USS *Freedom* (LCS 1) enlisted manpower level with the additional nine enlisted sailors "plus up." The third model (enlisted core crew of 48) was built to obtain comparative data on a notional LCS core crew of 60 sailors (assuming a core crew of 48 enlisted and 12 officers). To get this third condition with the notional enlisted core crew of 48, two enlisted sailors were added to each of the four LCS departments (i.e., Engineering, Combat Systems, Supply, and Operations).

2. Model Objective

The objective of the IMPRINT model is to assess the following questions: Can the IMPRINT Pro Forces module be used to determine manpower requirements for an LCS Force unit? Can the LCS enlisted core crew size of 31, 40, and/or 48 provide adequate manning to successfully complete all planned activities and unplanned events during a 21-day underway period? What differences, if any, are detected in failures between the three different manning levels?

3. Inputs to the Model

The data used to generate the IMPRINT Pro models was collected from multiple sources. The Center of Naval Analysis (CNA) supplied cards, in the form of excel spreadsheets, of data they gathered from the USS *Freedom* (LCS 1) deployment to Singapore March 1, 2013 to December 31, 2013 with Blue Crew 101 and Gold Crew 102. This case study only used the underway data for LCS 1 Blue Crew due to incomplete data in several critical categories from the Gold Crew. In-port data was also excluded because USN ship manpower estimates are determined solely using at-sea workload (afloat workweek) and an LCS crew would be able to utilize shore support during in-port periods. The afloat workweek assumes an autonomous unit steaming in Condition III (wartime/deployed cruising readiness) on a three-section watch basis. The watch configurations for the IMPRINT Pro models included three-section watch rotations for the 31 and 40 enlisted core crew models and a four-section watch rotation for the 48 enlisted core crew model. Due to manning limitations, the enlisted core crews of 31 and 40 did not have enough personnel for a four-section watch rotation in all departments. The notional crew of 48 (total crew size of 60) does allow for a four-section watch rotation in all four departments.

The CNA data cards, shown in Figure 8, display a snapshot of all sailors onboard LCS 1, alphabetically and by rate, during deployed, underway periods.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Crew	Billet #	Core?	Dept	Name	Rating type	Rank	Date	PM hours	CM hours	Watch Station	Watch hours	watch start time	Drill hours
2	Blue	12	Core	Operations	BM2	BM	E5	08/09/13	2	0		0		4
3	Blue	13	Core	Operations	BM3	BM	E4	08/09/13						
4	Blue	11	Core	Operations	BMCS	BM	E8	08/09/13	0	0		0		2
5	Blue	51	Plus10	Operations	BMSR	BM	E3	08/09/13	3	0		0		4
6	Blue	37	Core	Supply	CS1	CS	E6	08/09/13	1	0	DUTY CS	20	4AM	3
7	Blue	47	Plus10	Supply	CS3	CS	E4	08/09/13	0	0	DUTY CS	17	6AM	0
8	Blue	36	Core	Supply	CSC	CS	E7	08/09/13	0	0		0		3
9	Blue	38	Core	Supply	CSSN	CS	E3	08/09/13	0	0	DUTY CS	17	4AM	0
10	Blue	52	Plus10	Engineering	DC3	DC	E4	08/09/13	6	0		0		2
11	Blue	33	Core	Engineering	DCC	DC	E7	08/09/13	2	8		4	1200	0
12	Blue	32	Core	Engineering	EM1	EM	E6	08/09/13						
13	Blue	45	Plus10	Engineering	EM2	EM	E5	08/09/13	0	16		0		0
14	Blue	30	Core	Engineering	EN1#1	EN	E6	08/09/13	0	10	RCO	10		0
15	Blue	29	Core	Engineering	EN1#2	EN	E6	08/09/13	4	9		10	7AM,5PM	0
16	Blue	31	Core	Engineering	EN1#3	EN	E6	08/09/13	0	10		8		0
17	Blue	48	Plus10	Engineering	EN2	EN	E5	08/09/13	0	9		10		0
18	Blue	26	Core	Engineering	ENC	EN	E7	08/09/13						
19	Blue	22	Core	Combat Systems	ET1#1	ET	E6	08/09/13	0	2		0		3
20	Blue	24	Core	Combat Systems	ET1#2	ET	E6	08/09/13						
21	Blue	17	Core	Combat Systems	ET1#3	ET	E6	08/09/13	1	3.5		0		4
22	Blue	23	Core	Combat Systems	FC1#1	FC	E6	08/09/13	1	0	DSO	5	2AM	2
23	Blue	18	Core	Combat Systems	FC1#2	FC	E6	08/09/13	0	0	GFCS	17	0700-2200	0
24	Blue	16	Core	Combat Systems	FC1#3	FC	E6	08/09/13	1	0	DSO	11		0
25	Blue	15	Core	Combat Systems	FCC	FC	E7	08/09/13	1	0		4	2200	1.5
26	Blue	19	Core	Combat Systems	GM1#1	GM	E6	08/09/13	1.5	0	DORNA	11	3AM,6PM	1
27	Blue	49	Plus10	Combat Systems	GM1#2	GM	E6	08/09/13	1	0	SCAT	2		1
28	Blue	20	Core	Combat Systems	GM2	GM	E5	08/09/13						
29	Blue	27	Core	Engineering	GSE1	GSE	E6	08/09/13	0	0	RCO	10	2100	0
30	Blue	28	Core	Engineering	GSM2	GSM	E5	08/09/13	0	3	EPT	10	2AM,12PM	0
31	Blue	34	Core	Supply	HM1	HM	E6	08/09/13	3	0		0		0
32	Blue	44	Plus10	Engineering	HT1	HT	E6	08/09/13						
33	Blue	9	Core	Combat Systems	ITC #1	IT	E7	08/09/13						
34	Blue	10	Core	Combat Systems	ITC #2	IT	E7	08/09/13	2	7.5		12		1

Figure 8. Snapshot of LCS 1 data cards
(from Center of Naval Analysis, 2013)

The CNA data cards were completed daily by crewmembers. The information on the data cards was divided into several categories including the following (Figure 9):

Preventative maintenance hours
Corrective maintenance hours
Corrective maintenance system
Watch station
Watch hours
Watch start time
Drill hours
Drills performed
Special evolution hours
Special evolutions involved in
Training hours
Meeting hours
Total sleep hours
Sleep breakdown hours
Downtime hours
What qualification was achieved

Figure 9. CNA data card categories

Inputs to the IMPRINT Pro models required detailed knowledge of underway shipboard activities for planned activities and unplanned events, to include duration and timing of each event. Crew feedback, in the form of a survey administered to crew members of the USS *Independence* (LCS 2), served to correct inaccuracies and update model inputs. This information was compiled and then submitted to current LCS operations officer, LCDR Matthew L. Muehlbauer, USN, for external verification and validation.

4. IMPRINT Pro Forces Model Design

An eight-step process was used to create each of the IMPRINT Pro Forces models. These steps are (1) define the force unit of interest, (2) develop a list of planned activities to be performed by the force unit, (3) develop a list of unplanned events to be performed by the force unit, (4) define schedules for the force unit, (5) develop a list of jobs comprising the force unit, (6) assign roles to the jobs, (7) set the Activities Trump Matrix, and (8) run the Force Analysis model to generate reports.

To define the force unit in step 1, the LCS Activities Manpower Document (AMD), discussed in Chapter II of the Literature Review on the Fleet Manpower Determination Process, was used to describe each rate for the original LCS enlisted core crew. Model 1, the core crew model with 31 enlisted sailors, reflected the original AMD for both variants of LCS, which reflects the current enlisted core crew on the USS *Independence* (LCS 2). Model 2, the core crew model with 40 enlisted sailors, was modeled after the data taken from the Center for Naval Analysis (CNA) documenting the "plus up" of nine enlisted sailors aboard the USS *Freedom* (LCS 1) during the 2013 deployment to Singapore. Model 3, the core crew model with 48 enlisted sailors, was built with two enlisted sailors added to each of the four departments on LCS to reflect a notional enlisted core crew size of 60 (i.e., 48 enlisted sailors and 12 officers).

Step 2, developing a list of planned activities, entailed creating schedules for the crew based on watch rotation (either two- or three-section watchbill) and typical events encountered on a daily basis aboard the LCS. Each model was built as a deployed unit steaming in Condition III, using either a three-section "five and dime" or four-section watch rotation for a total of 21 days. Since some LCS watch stations are not able to support a three-section watch rotation due to the limited number of qualified personnel available in the 31 and 42 enlisted core crew models, a two-section watch rotation was created to supplement as shown in Figure 10. For all three models, schedules were also created for those personnel who do not stand watch.

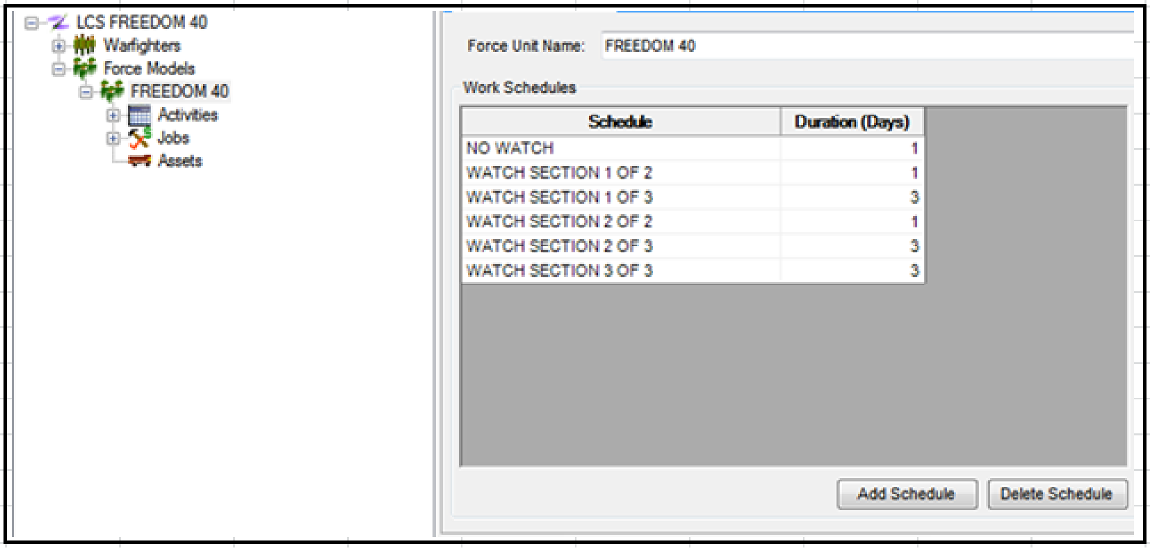


Figure 10. Snapshot of LCS 1 watch schedules

Steps 2 and 3 required a list of planned activities and unplanned events to be developed to simulate what events a unit would potentially encounter during a 21-day underway. The red blocks in Figure 11 show those planned activities the crew is expected to complete daily, such as standing watch, training, personal hygiene, sleeping, and eating. The unplanned events are represented by the yellow tags in Figure 11 and represent emergencies that disrupt the daily routine. The planned activities are scheduled with start and end times, while the unplanned events have randomized start times.

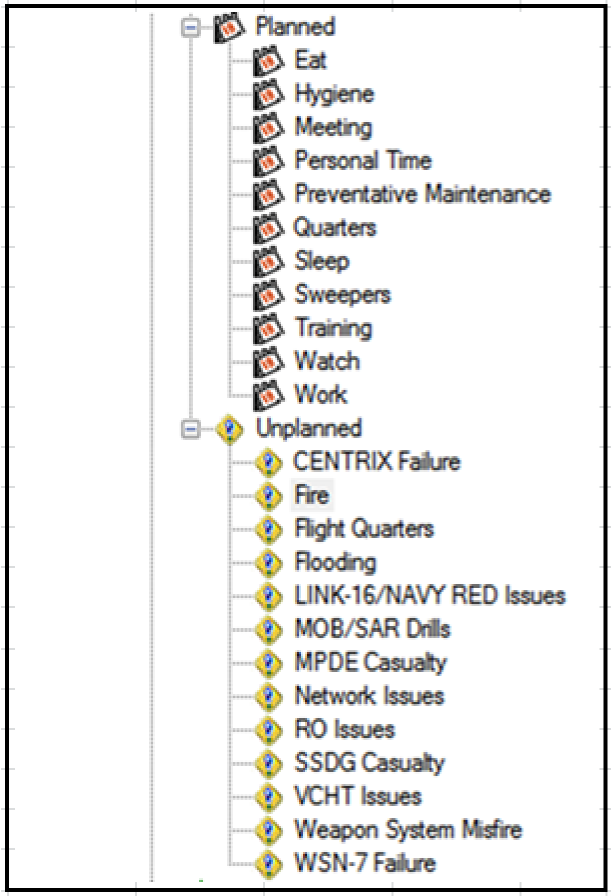


Figure 11. Planned and unplanned activities

Figure 12 shows the attributes of an unplanned event that are captured in the IMPRINT Tool. The example illustrated is for a shipboard fire, just one possible unplanned event that could occur during a typical underway period.

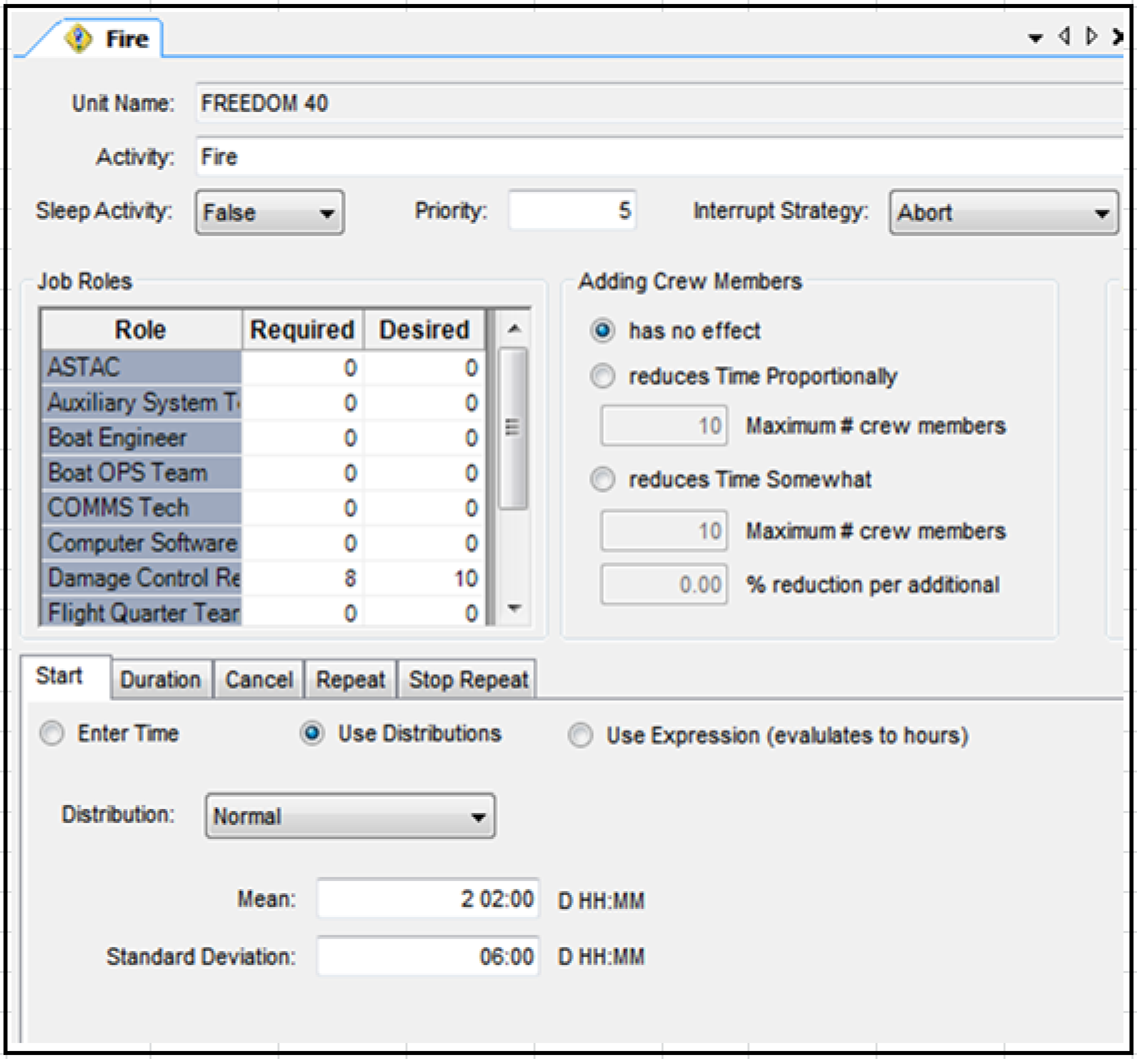


Figure 12. Attributes of an unplanned fire

The attributes of unplanned events have the following fields:

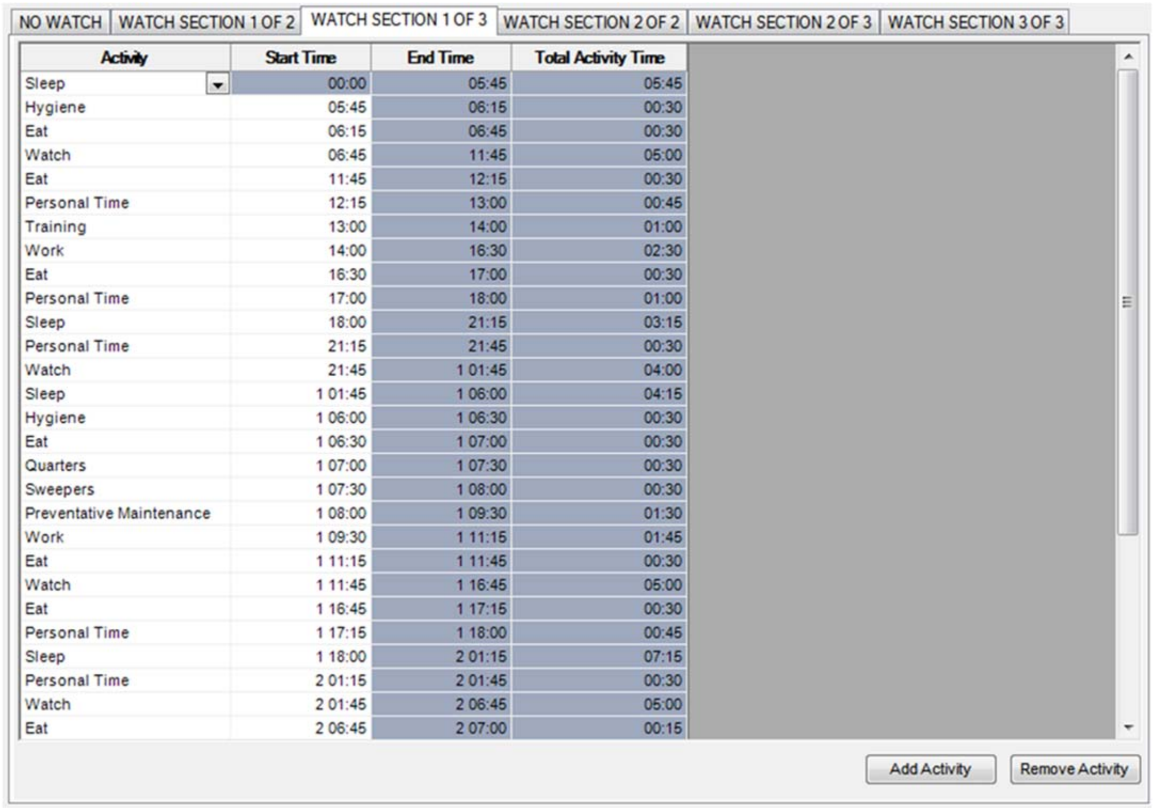
- Sleep activity
- Interrupt strategy
- Job roles
- Adding crew members
- Start
- Duration
- Repeat times

The interrupt strategy allows the user to set the priority of an activity or event if the personnel required for the planned activity or event are taken up by a higher priority. Job roles are positions that respond to the planned activity or unplanned event and also display how many people are required and desired. The start time is the day and time when the planned activity or unplanned event should start, followed by the duration, which is the expected duration of the activity or event, and ending with the repeat time, which is the interval at which this activity or event repeats. All times entered are based on a mean and standard deviation so that there is variation in the models.

Step 4 requires a schedule to be defined for each core crewmember. Defining the schedule is a critical part of the IMPRINT modeling process because the simulated sailors in each of their jobs will follow this schedule when the model simulation is run. All daily, planned activities used to define schedules were entered based on the CNA data cards collected during the 2013 underway. These were reviewed and refined by actual LCS crewmember (LCDR Matthew L. Muehlbauer, USN), and the prior experience of LT Hollins, a qualified Surface Warfare Officer. The following assumptions were made for certain aspects of each schedule for all three models:

- One hour of personal time was given following lunch and dinner
- Thirty minutes was allotted for each meal
- No work was conducted between the hours of 1800 and 0600
- Conventional Navy watchbills were used for both two-, three-, and four-section watches (port and starboard 6/6, five and dimes 5/10, and 5/15).

Figure 13 shows a snapshot of a daily schedule for the first watch section in a three-watch rotation. Each of the other watch sections had similar daily schedules, depending on the timing of the watch they were standing.



Activity	Start Time	End Time	Total Activity Time
Sleep	00:00	05:45	05:45
Hygiene	05:45	06:15	00:30
Eat	06:15	06:45	00:30
Watch	06:45	11:45	05:00
Eat	11:45	12:15	00:30
Personal Time	12:15	13:00	00:45
Training	13:00	14:00	01:00
Work	14:00	16:30	02:30
Eat	16:30	17:00	00:30
Personal Time	17:00	18:00	01:00
Sleep	18:00	21:15	03:15
Personal Time	21:15	21:45	00:30
Watch	21:45	1 01:45	04:00
Sleep	1 01:45	1 06:00	04:15
Hygiene	1 06:00	1 06:30	00:30
Eat	1 06:30	1 07:00	00:30
Quarters	1 07:00	1 07:30	00:30
Sweepers	1 07:30	1 08:00	00:30
Preventative Maintenance	1 08:00	1 09:30	01:30
Work	1 09:30	1 11:15	01:45
Eat	1 11:15	1 11:45	00:30
Watch	1 11:45	1 16:45	05:00
Eat	1 16:45	1 17:15	00:30
Personal Time	1 17:15	1 18:00	00:45
Sleep	1 18:00	2 01:15	07:15
Personal Time	2 01:15	2 01:45	00:30
Watch	2 01:45	2 06:45	05:00
Eat	2 06:45	2 07:00	00:15

Figure 13. Daily work schedule for watch section 1 of 3

Once the planned activities and unplanned events were defined, a list of jobs for each unit was created. The sailors in this model were assigned jobs based on their military occupational specialty as shown in Figure 14. This job assignment was based on the CNA data cards and the LCS 2 AMD which listed the required personnel needed to fill the jobs in each model. Once the jobs were defined, job roles were assigned. Job roles are the specific positions filled by the sailors. Data collected by CNA and feedback that was solicited from LCS 2 crewmembers were the sources of information used to assign roles to each sailor in each of the three models.

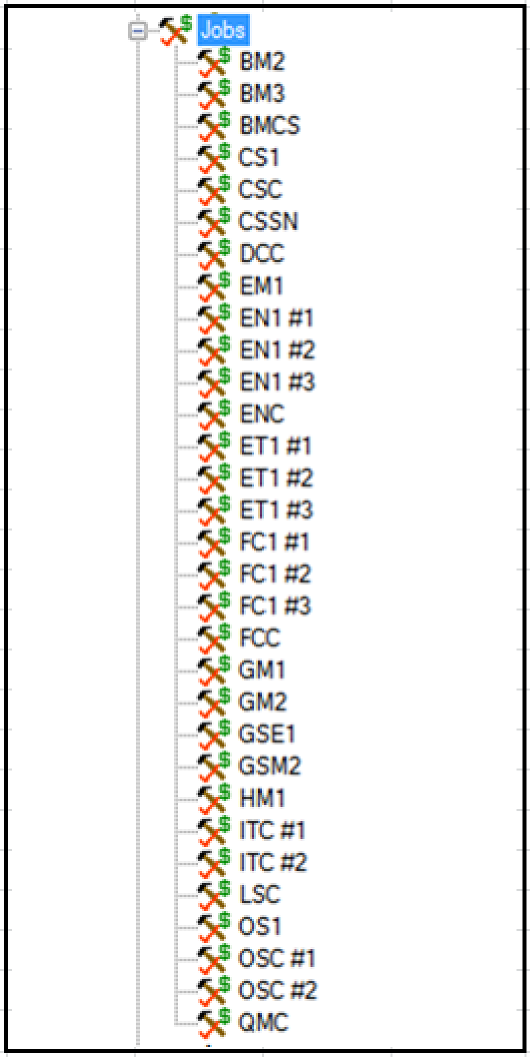


Figure 14. List of jobs

During the simulation, many activities are initiated at the same time, but since the number of sailors is limited, sailors can only perform one activity at a time according to the Activity Trump Matrix. Step 7 sets up the Activities Trump Matrix, and is a critical step because it establishes the priority in which planned activities and unplanned events are engaged, ensuring that the sailors are addressing more important activities or events first. If a sailor is assigned more than one activity or event at a time, the activity or event with a higher priority will be addressed first. Figure 15 displays the trump matrix used in each model. For example, if a sailor is sleeping and a fire starts, the sailor will wake up and engage the fire if they are assigned to a job role that responds to fires. Likewise, if a sailor is eating and flight quarters is called, the sailor will stop eating and attend flight quarters if they are assigned to a job role that responds to flight quarters. The same Activity Trump Matrix was used for each model.

Activities

Priority	Name	Type
0	Watch	Planned
1	MOB/SAR Drills	Unplanned
5	Fire	Unplanned
10	Flooding	Unplanned
20	SSDG Casualty	Unplanned
30	MPDE Casualty	Unplanned
60	Flight Quarters	Unplanned
70	RO Issues	Unplanned
80	VCHT Issues	Unplanned
90	WSN-7 Failure	Unplanned
100	LINK-16/NAVY RED Issues	Unplanned
110	Network Issues	Unplanned
120	CENTRIX Failure	Unplanned
130	Weapon System Misfire	Unplanned
190	Preventative Maintenance	Planned
195	Sleep	Planned
200	Eat	Planned
210	Work	Planned
260	Training	Planned
270	Meeting	Planned
275	Sweepers	Planned
281	Personal Time	Planned
300	Quarters	Planned
320	Hygiene	Planned

Figure 15. Activities Trump Matrix

In step 8, the authors ran 100 iterations of each of the three core crew model simulations. The outputs from all of these simulated runs were exported into Excel spreadsheets by the IMPRINT Pro Forces module. The execution setting for this case study was set to 21 days in length. This setting was selected because, according to OPNAVINST 3501.352 (a rough draft of the LCS ROC/POE), the LCS maximum expected crew endurance for Condition III steaming is 21 consecutive days, with the opportunity for 8 hours of rest per crewmember per day.

For each model, the same random seed number (RSN) was used for all three models during the first run; for each subsequent run, a different RSN was used for all three models. For example, the first run for each model used the RSN of 1. The second run of all three models used a different RSN than that used in run one but again, the RSN was set the same for all three models. The RSN was different for each of the 100 runs to simulate model variation in results.

Upon successful completion of a run, IMPRINT Pro generated a number of pre-selected reports as shown in Figure 16. The Unplanned Activity Status report, shown in Figure 17, was the primary report used for this case study since it provides information on how many planned activities or unplanned events failed within a specified time period and what specific job roles failed to complete the activity or event.

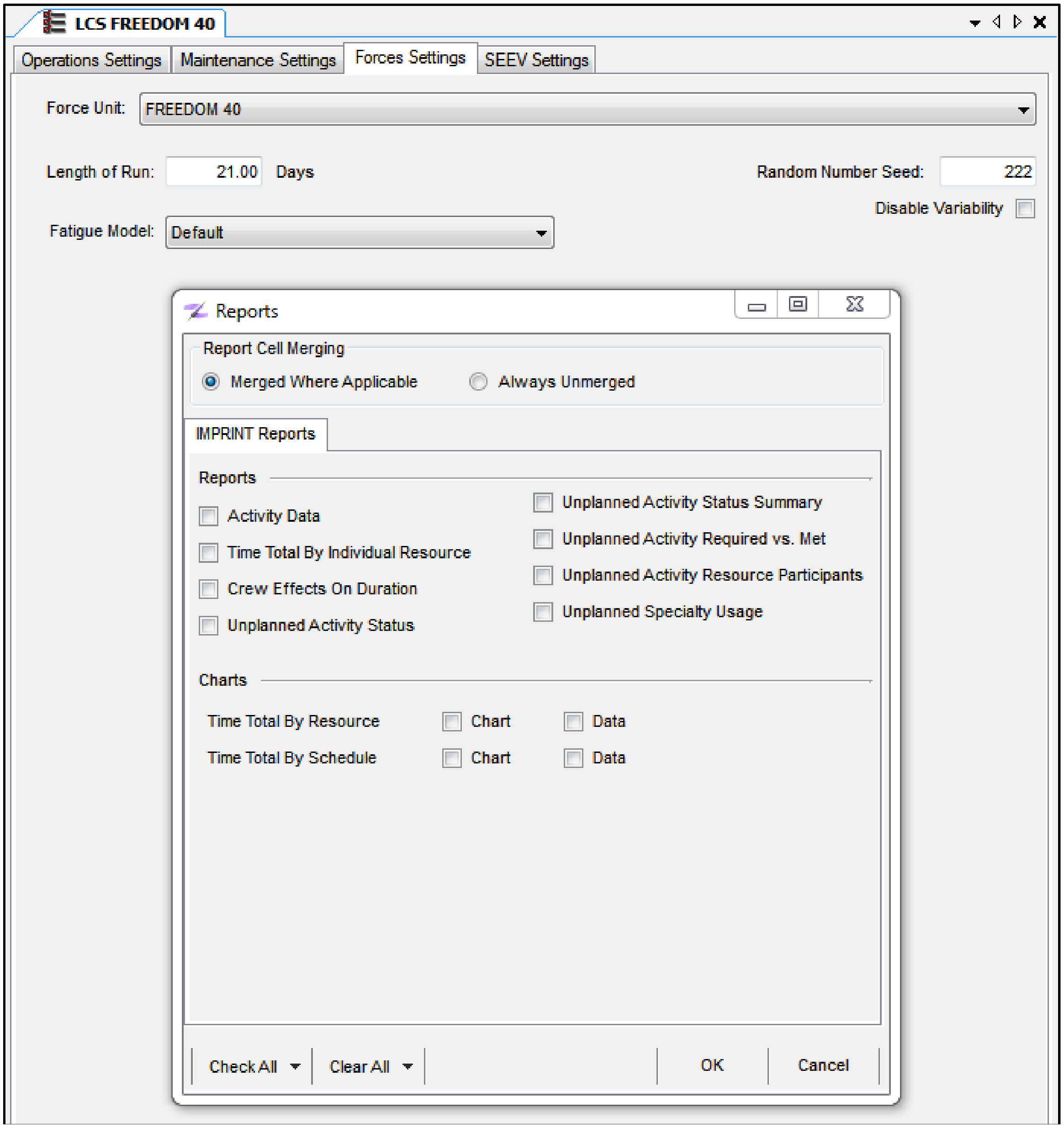


Figure 16. Display of execution settings and reports selection tables

IMPRINT Forces Model Report
Unplanned Activity Status

Analysis:	LCS FREEDOM 40				
Force Unit:	FREEDOM 40				
RNS:	43				
Date:	12-Feb-14				
			(Hours)		
	Unplanned Activity	**Unique ID**	**Simulation Time**	**Activity Status**	**Roles and Features Unmet**
	WSN-7 Failure	-11	36.9566	Scheduled	
	WSN-7 Failure	-11	36.9566	Started	
	LINK-16/NAVY RED Issues	-12	39.4339	Scheduled	
	LINK-16/NAVY RED Issues	-12	39.4339	Failed	COMMS Tech
	WSN-7 Failure	-11	39.8995	Successful	
	CENTRIX Failure	-9	44.9638	Scheduled	
	CENTRIX Failure	-9	44.9638	Started	
	CENTRIX Failure	-9	47.6558	Successful	
	Fire	-1	58.6053	Scheduled	
	Fire	-1	58.6053	Started	
	Fire	-1	60.6405	Successful	
	LINK-16/NAVY RED Issues	-14	62.7513	Scheduled	
	LINK-16/NAVY RED Issues	-14	62.7513	Started	
	LINK-16/NAVY RED Issues	-14	63.3101	Successful	
	Flight Quarters	-6	89.3619	Scheduled	
	Flight Quarters	-6	89.3619	Started	
	Flooding	-2	89.5113	Scheduled	
	Flooding	-2	89.5113	Started	
	Flight Quarters	-6	89.5113	Interrupted	
	Flooding	-2	92.5853	Successful	
	LINK-16/NAVY RED Issues	-15	95.1667	Scheduled	
	LINK-16/NAVY RED Issues	-15	95.1667	Failed	COMMS Tech
	Weapon System Misfire	-13	98.8888	Scheduled	
	Weapon System Misfire	-13	98.8888	Failed	Weapon System Tech
	LINK-16/NAVY RED Issues	-16	107.0554	Scheduled	
	LINK-16/NAVY RED Issues	-16	107.0554	Failed	COMMS Tech
	MOB/SAR Drills	-5	109.3929	Scheduled	
	MOB/SAR Drills	-5	109.3929	Failed	MOB Rescue Teams, Boat OPS Team

Figure 17. Unplanned activity status report

C. FATIGUE AVOIDANCE SCHEDULING TOOL METHOD

1. Overview

The FAST program was used in this study to predict cognitive effectiveness based on sleep and work patterns over a 21-day underway period. FAST calculates the impact that the 72-hour sleep history has on a given individual's alertness and cognitive effectiveness at any point in the schedule. Actual sleep data from LCS crewmembers was not used in this thesis, but FAST also allows for analysis of manpower using both actual sleep data as well as notional data.

2. FAST Objectives

FAST was utilized to help draw conclusions about the watch rotations used by LCS 1 and LCS 2. The IMPRINT Pro Forces module results do not show the effectiveness of the individual throughout a period of time. The objective of this case study, in regards to FAST, is to examine what effect sleep schedules and watch rotations used onboard the USS *Freedom* (LCS 1) and USS *Independence* (LCS 2) have on a sailor's cognitive effectiveness, and to illustrate the expected individual effectiveness of a sailor. By using the watch and sleep schedules derived from the IMPRINT model simulations, FAST results give an approximation of the effectiveness level a sailor will experience when executing their daily activities and unplanned events.

3. Data for FAST Input

The FAST inputs for this case study were taken from watch rotations currently used afloat. Two-section, three-section, and four-section watch schedules were simulated using FAST. Three-section and four-section watch rotations are the most common in the fleet. Typically, a two-section watch rotation is used when a ship does not have the manpower support or does not have enough qualified sailors. FAST was also used to illustrate sleep and watch schedules depicted in the IMPRINT Pro Forces simulations. No actual sleep data were collected; all sleep and work intervals and watch rotations are notional.

Using the results from the IMPRINT Pro Forces models, the sailor with the most sleep and the sailor with the least sleep was modeled in FAST using the watch and sleep times simulated by IMPRINT Pro Forces. First, a random model run was chosen from the 100 simulations of each IMPRINT model (RSN 3). Then the sailor with the highest average sleep amount and the sailor with the least average sleep amount was chosen and their 21-day schedules were modeled in FAST. When imputing IMPRINT schedule data into FAST, a sailor was assumed to be working if free time was encountered between 0600–1800. For example, if a sailor on a three-section watch rotation has just finished standing watch from 0200–0700, that sailor will then go to work. This situation is a typical occurrence during watch rotations while underway. The FAST outputs that illustrate the most sleep amount and least sleep amount of an enlisted sailor found in each enlisted core crew model are shown in Figures 37 to 42, the FAST Results section of Chapter IV.

4. FAST Schedule Design

The first step in the FAST process is to enter the schedule properties, as shown in Figure 17, and enter the name of the schedule. For this case study, the name of the schedule is the actual watch rotation. The description box is not a required field. The next step involves filling in the descriptive information, such as when the schedule will start, the duration of the schedule, and the location. FAST is meant to supplement this case study by determining cognitive performance at the individual level; because LCS 1 data was collected while on deployment in Singapore, Singapore was the geographic location selected in FAST (as shown in Figure 18). Geographic location in FAST is important since it accounts for the actual times of sunrise and sunset, and provides insight into light cues and daylight savings time.

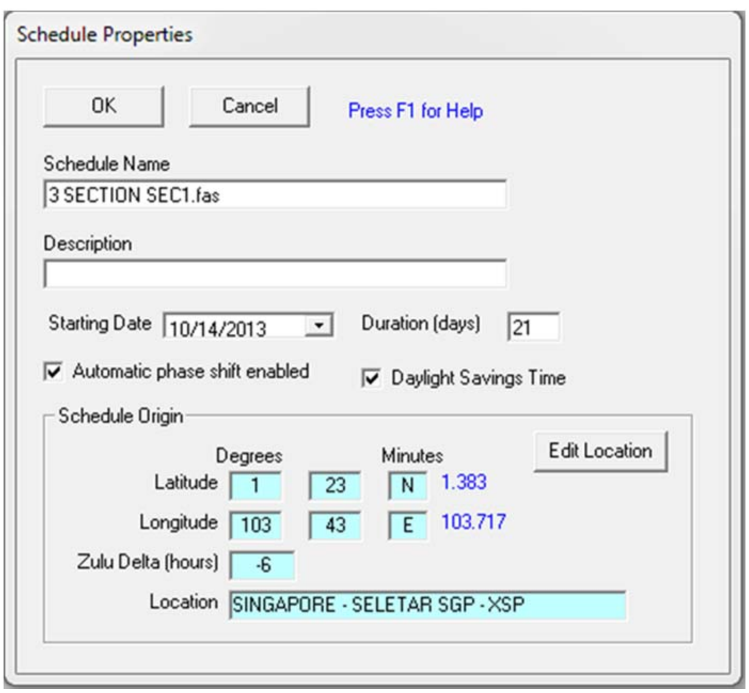
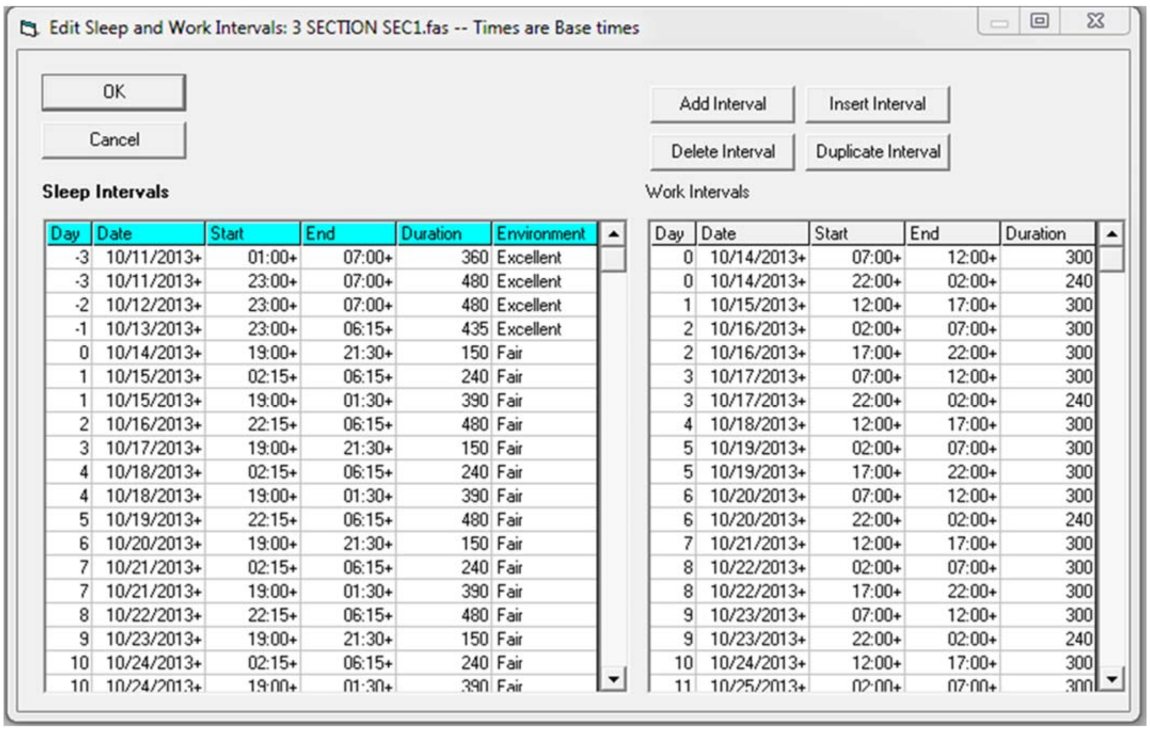


Figure 18. Edit schedule properties window

In the next step, the schedule information must be defined. FAST has two methods to accomplish this schedule definition. The two methods are the *sleep and work interval table* method (Figure 19) and the *schedule grid* method (Figure 20). Either method is effective since once you enter data using one of the methods, FAST automatically populates the other table. In this study, the *schedule grid* method was used to input work and sleep data.



Sleep Intervals

Day	Date	Start	End	Duration	Environment
-3	10/11/2013+	01:00+	07:00+	360	Excellent
-3	10/11/2013+	23:00+	07:00+	480	Excellent
-2	10/12/2013+	23:00+	07:00+	480	Excellent
-1	10/13/2013+	23:00+	06:15+	435	Excellent
0	10/14/2013+	19:00+	21:30+	150	Fair
1	10/15/2013+	02:15+	06:15+	240	Fair
1	10/15/2013+	19:00+	01:30+	390	Fair
2	10/16/2013+	22:15+	06:15+	480	Fair
3	10/17/2013+	19:00+	21:30+	150	Fair
4	10/18/2013+	02:15+	06:15+	240	Fair
4	10/18/2013+	19:00+	01:30+	390	Fair
5	10/19/2013+	22:15+	06:15+	480	Fair
6	10/20/2013+	19:00+	21:30+	150	Fair
7	10/21/2013+	02:15+	06:15+	240	Fair
7	10/21/2013+	19:00+	01:30+	390	Fair
8	10/22/2013+	22:15+	06:15+	480	Fair
9	10/23/2013+	19:00+	21:30+	150	Fair
10	10/24/2013+	02:15+	06:15+	240	Fair
10	10/24/2013+	19:00+	01:30+	390	Fair

Work Intervals

Day	Date	Start	End	Duration
0	10/14/2013+	07:00+	12:00+	300
0	10/14/2013+	22:00+	02:00+	240
1	10/15/2013+	12:00+	17:00+	300
2	10/16/2013+	02:00+	07:00+	300
2	10/16/2013+	17:00+	22:00+	300
3	10/17/2013+	07:00+	12:00+	300
3	10/17/2013+	22:00+	02:00+	240
4	10/18/2013+	12:00+	17:00+	300
5	10/19/2013+	02:00+	07:00+	300
5	10/19/2013+	17:00+	22:00+	300
6	10/20/2013+	07:00+	12:00+	300
6	10/20/2013+	22:00+	02:00+	240
7	10/21/2013+	12:00+	17:00+	300
8	10/22/2013+	02:00+	07:00+	300
8	10/22/2013+	17:00+	22:00+	300
9	10/23/2013+	07:00+	12:00+	300
9	10/23/2013+	22:00+	02:00+	240
10	10/24/2013+	12:00+	17:00+	300
11	10/25/2013+	02:00+	07:00+	300

Figure 19. Edit sleep and work intervals table

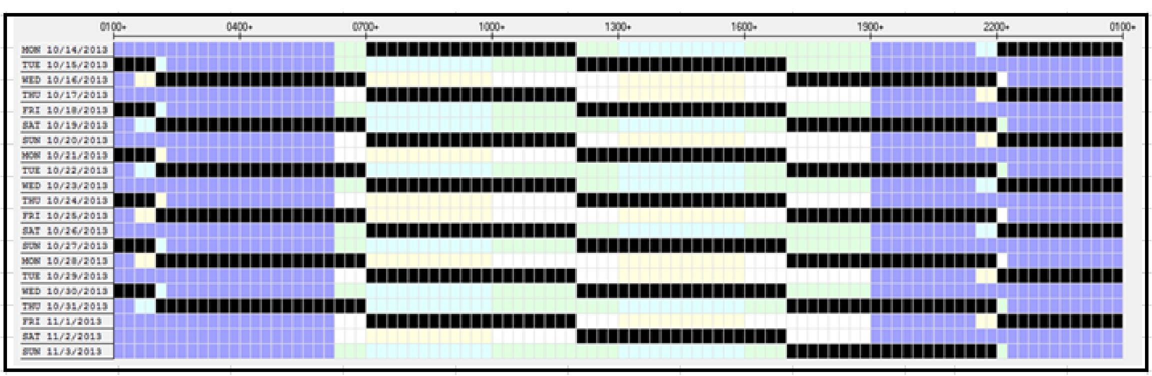


Figure 20. Schedule grid example

The final two steps of the FAST model setup involved editing the graphical display options and displaying the results. On the graphical display options table, there are four fields to populate: (1) *time display*, (2) *scale minimum*, (3) *zone limits and criterion line*, and (4) *right axis scale*. The *time display* offers the option of setting the time to local, Zulu, or a mission-specific time. The *minimum scale* field refers to the minimum value required on the Y-axis of the display, as shown in Figures 21 and 22. The *zone limits and criterion line* fields represent the ranges of performance and were left on the default settings provided in FAST.

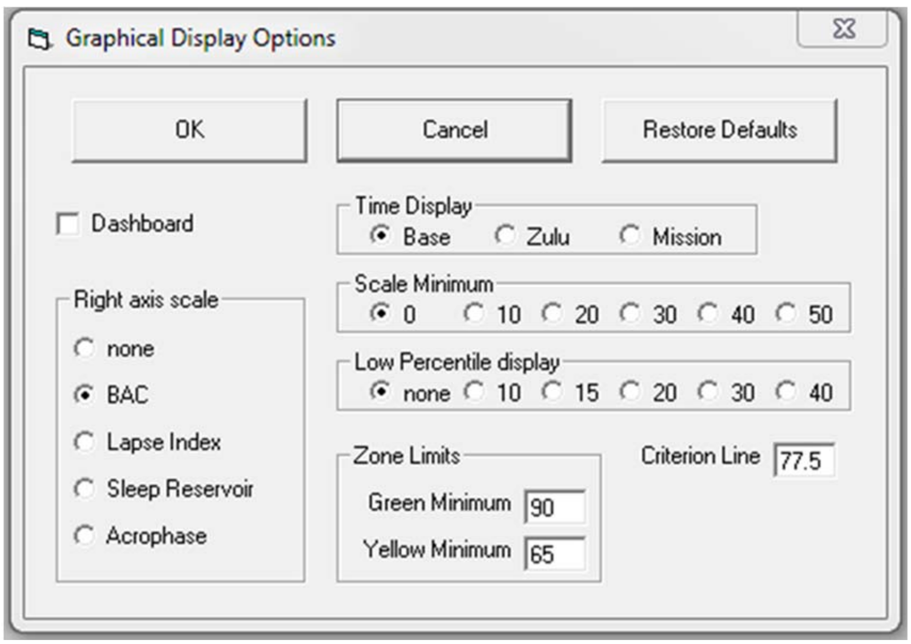


Figure 21. Graphical display options

In Figure 22, the horizontal green band at the top represents the predicted effectiveness of 90% or better. The performance of a person on a normal duty day with 8 hours of excellent sleep would fall into this green band. The yellow band below the green band represents predicted effectiveness of 77.5–90%, a cautionary zone that indicates degraded performance. The red horizontal band represents predicted effectiveness levels less than 77.5% and also corresponds to the degraded vigilance performance common in a person who is severely sleep-deprived.

The vertical scale on the right axis scale has multiple metrics to display to depict how the individual is performing. Two of the more commonly used metrics are the lapse likelihood index and the blood alcohol concentration (BAC) scale. The BAC scale, seen on the right axis, was used in this study to show that, at certain periods, predicted effectiveness was equivalent to that of a person who is intoxicated. When all these fields are completed, FAST generates a graphical depiction of an individual's cognitive performance for the specified period.

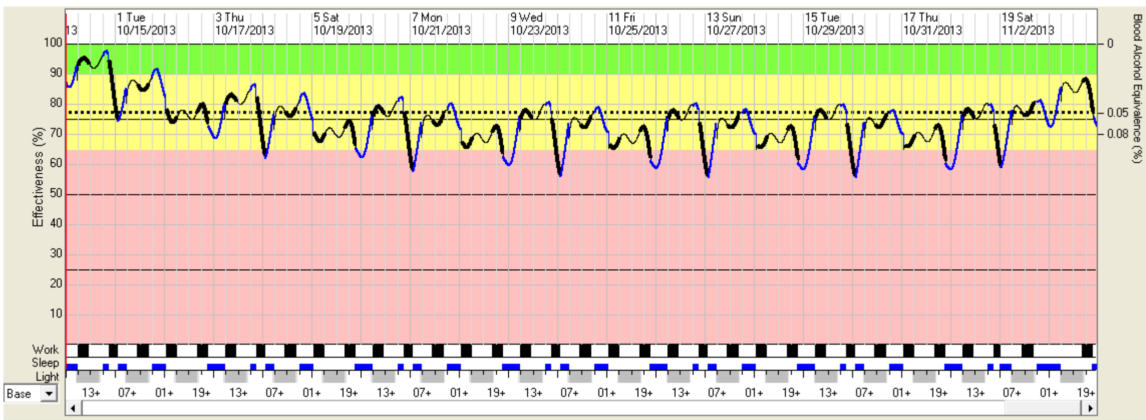


Figure 22. Example of graphical output of FAST

D. SURVEY

1. Overview

As a final step in this thesis, a survey was developed to administer to LCS crewmembers to validate the inputs used for the IMPRINT models and to assess the validity of the IMPRINT and FAST results. The survey was designed specifically to validate the results of the IMPRINT and FAST models to see if crewmembers' perceptions of departmental and individual workloads onboard LCS are reflected in the results of IMPRINT and FAST modeling efforts. This survey was important for two reasons: 1) it helped validate IMPRINT model inputs, such as watch rotations being used by departments onboard LCS; and 2) it allowed a comparison between the IMPRINT and FAST results and LCS sailor opinions.

2. Survey Objectives

A survey was developed and administered to Crew 202/GOLD aboard the USS *Independence* (LCS 2) in January of 2014. A total of 33 LCS sailors completed this baseline survey of certain aspects of the LCS during an operational underway period. The survey was administered to solicit personal opinions about the current watch rotations being used, the relative workload of departments and for various shipboard positions, and the amount of sleep the current watch rotation permits. No identifying information was asked other than the sailors' rate or rank. Participation was completely voluntary.

3. Survey Respondents

There were 33 survey respondents: 21 enlisted core crew, 3 core crew officers, and 9 non-core crew enlisted sailors. The total enlisted core crew aboard the USS *Independence* (LCS 2) was 32, and the total officer core crew was 8. Survey respondents represented 66% of the enlisted core crew and 38% of the officer core crew. Figures 23 and 24 show survey respondents by rank and by department. Gender was not asked nor specified.

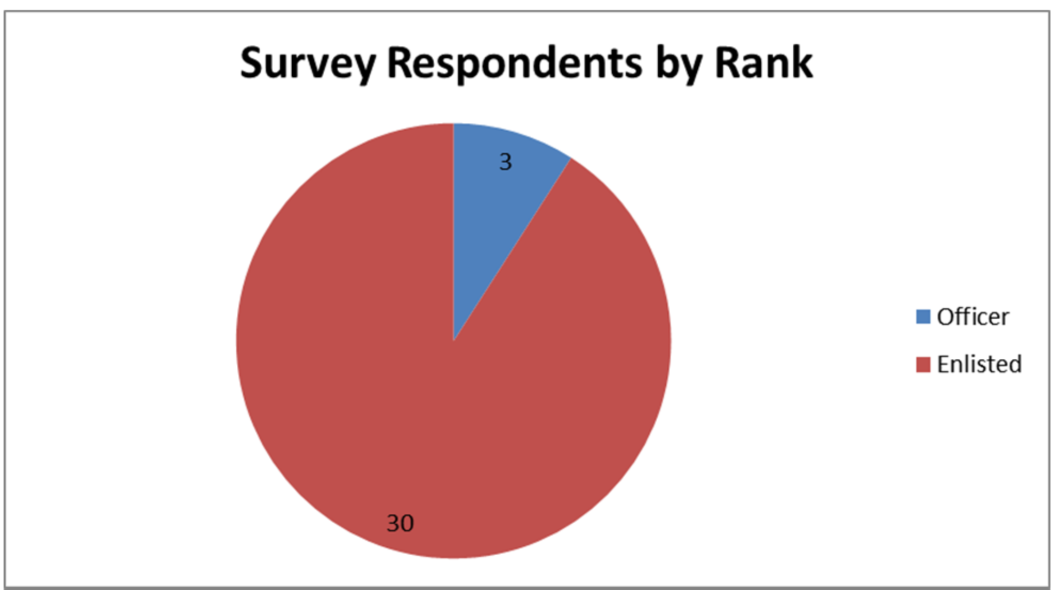


Figure 23. Survey participants by rank

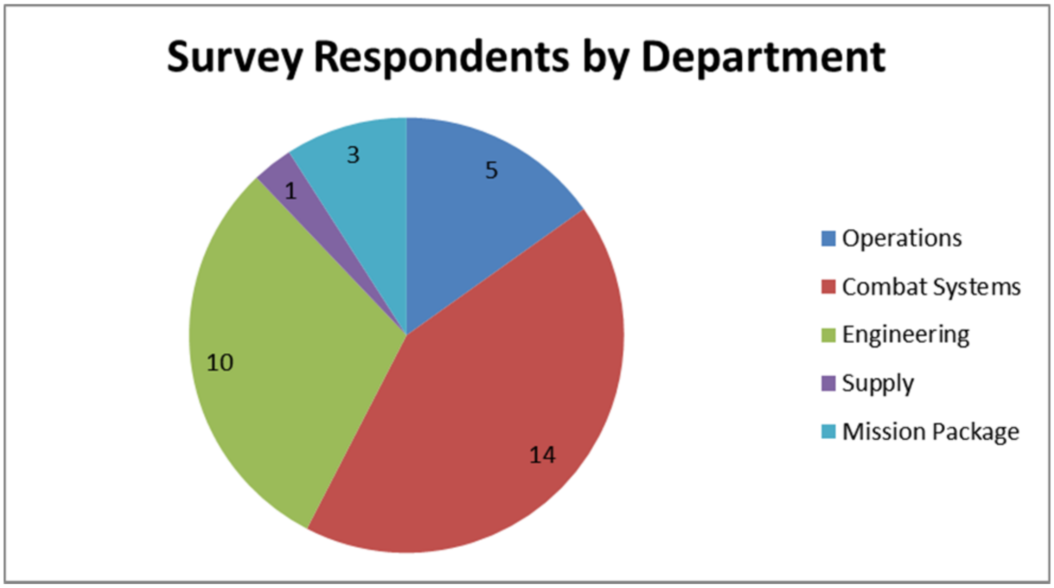


Figure 24. Survey participants by department

IV. RESULTS

This chapter explains and displays the results of the methods described in Chapter III. Section A presents the analysis of the IMPRINT Pro Forces data that determines if there are significant differences in failures of unplanned events among the three crew sizes. Section B presents the results of the predicted cognitive effectiveness, as calculated in FAST, of LCS sailors on watch in two-, three-, and four-section watch rotations and sailor performance during the IMPRINT simulation schedules. Section C presents the results of the LCS survey administered to USS *Independence* (LCS 2) crew.

A. IMPRINT PRO FORCES RESULTS

Upon completion of each model simulation run, IMPRINT Pro Forces generated an unplanned activity status report. The report displayed the unplanned activities, simulation time, activity status, and the roles and features that were unmet. The data collected from the unplanned activity status reports was used to calculate the mean time between failures (MTBF) and the average failures per run for each unplanned activity, shown in Tables 5 and 6. Each of the models ran 100 times to total 300 reports. The results from the MTBF and the average failure per run were used to compare the three sizes of enlisted core crews (i.e., 31, 40, and 48). A minimum of two failures is required to calculate the MTBF; consequently, we were unable to calculate the MTBF and average number of failures per run for fire, flooding, and centrix failures because those events had fewer than two failures during the simulation.

Mean Time Between Failures table	31		40		48	
	Mean	Standard Dev	Mean	Standard Dev	Mean	Standard Dev
SSDG Casualty	60.22	31.11	50.85	14.51	No Failures	No Failures
Weapon System Misfire	129.42	23.02	136.71	35.04	No Failures	No Failures
MPDE Casualty	161.31	126.97	261.41	154.01	No Failures	No Failures
LINK-16/NAVY RED Issues	58.32	21.56	No Failures	No Failures	No Failures	No Failures
Network Issues	78.81	70.45	No Failures	No Failures	No Failures	No Failures
RO Issues	372.95	0.76	No Failures	No Failures	No Failures	No Failures
VCHT Issues	297.98	7.49	No Failures	No Failures	No Failures	No Failures
WSN-7 failure	49.24	4.19	No Failures	No Failures	No Failures	No Failures
Centrix Failure	458.27*	No Failures	No Failures	No Failures	No Failures	No Failures
Fire	No Failures	No Failures	No Failures	No Failures	No Failures	No Failures
Flooding	No Failures	No Failures	No Failures	No Failures	No Failures	No Failures

Table 5. Mean time between failures for unplanned events

Average Number of Failures per Run	31		40		48	
	Avg Failure	Standard Dev	Avg Failure	Standard Dev	Avg Failure	Standard Dev
Weapon System Misfire	0.50	0.58	0.30	0.56	No Failures	No Failures
MPDE Casualty	0.71	0.74	0.20	0.43	No Failures	No Failures
SSDG Casualty	1.41	1.21	0.34	0.63	No Failures	No Failures
LINK-16/NAVY RED Issues	6.59	2.21	No Failures	No Failures	No Failures	No Failures
Network Issues	2.02	1.14	No Failures	No Failures	No Failures	No Failures
RO Issues	0.42	0.50	No Failures	No Failures	No Failures	No Failures
VCHT Issues	0.25	0.44	No Failures	No Failures	No Failures	No Failures
WSN-7 failure	0.56	4.90	No Failures	No Failures	No Failures	No Failures

Table 6. Average number of failures per run for unplanned events

An analysis of variance (ANOVA) test was conducted to determine statistically significant differences for each failed unplanned activity; then a Tukey Honestly Significant Difference (HSD) test was completed to determine where differences between core crews existed. The null hypothesis for this study stated that all the mean times between failures were the same for all three crew sizes; the alternative hypothesis assumed that two or more means were different from the others:

$$H_0: \mu_{31} = \mu_{40} = \mu_{48}, \text{ all the means are the same}$$

$$H_1: \mu_{31} \neq \mu_{40} \neq \mu_{48}, \text{ two or more means are different}$$

POST HOC TUKEY TEST	Statistically Significant Differences Between Core Crews (p< .05)		
	(31,40)	(40,48)	(31,48)
LINK-16/NAVY RED Issues	YES	NO	YES
Weapon System Misfire	NO	YES	YES
Network Issues	YES	NO	YES
RO Issues	YES	NO	YES
MPDE Casualty	NO	YES	YES
SSDG Casualty	NO	YES	YES
VCHT Issues	YES	NO	YES
WSN-7 failure	YES	NO	YES

Table 7. Tukey HSD test results

In Figures 25–32, the bars indicate mean comparisons between the two enlisted core crews. The narrow lines indicate the confidence intervals. If the confidence intervals exclude zero (i.e., the confidence interval does not cross the x-axis), there is a significant difference between the two enlisted core crews. If the confidence interval includes zero (crosses the x-axis), there is no statistical difference between the enlisted core crews. For example, Figure 25 shows the Tukey results for the Link failures with significant differences between core crew 31 as compared to core crew sizes 40 and 48. However, core crew size 40 was not different from 48.

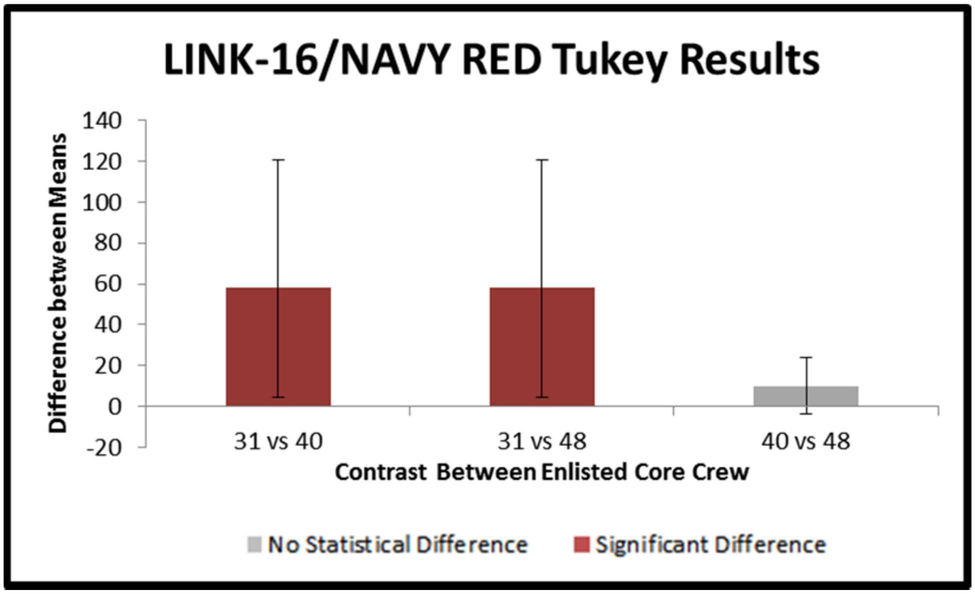


Figure 25. Link Tukey results

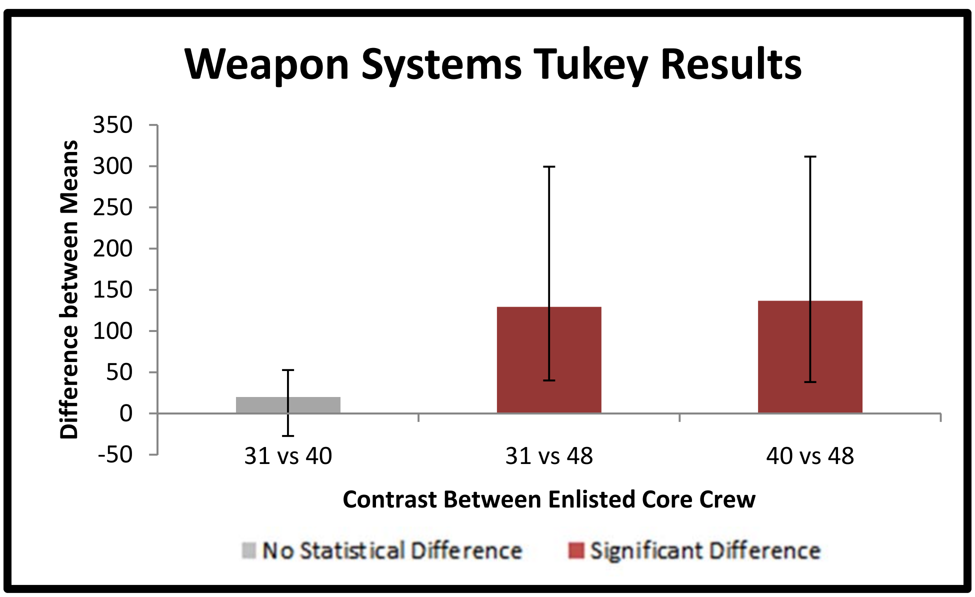


Figure 26. Weapon systems Tukey results

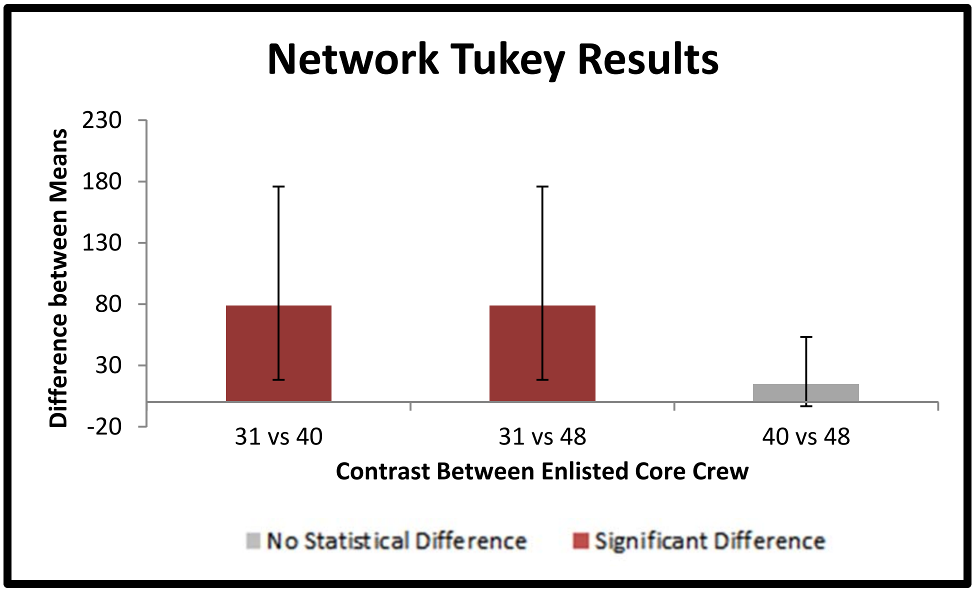


Figure 27. Network Tukey results

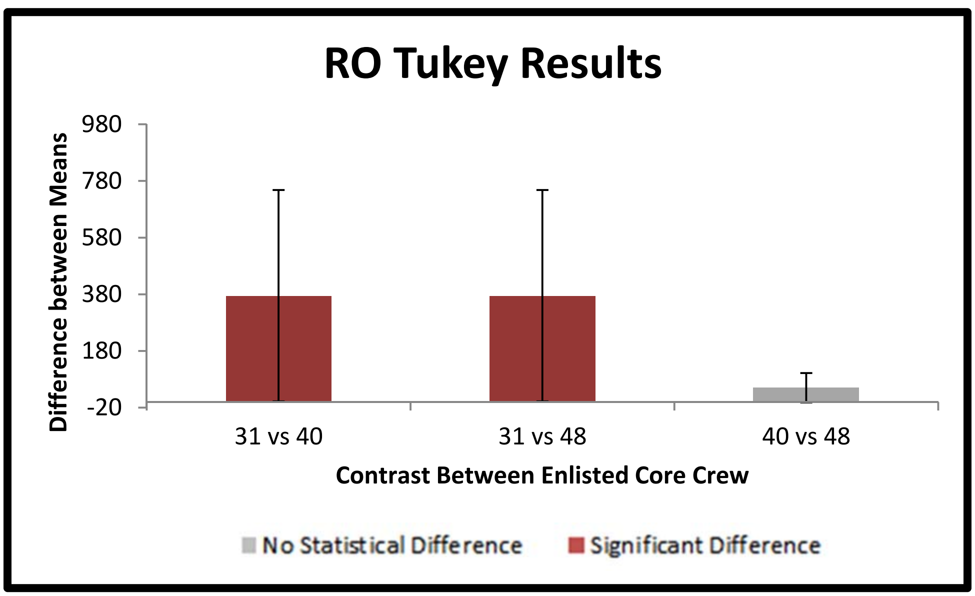


Figure 28. RO Tukey results

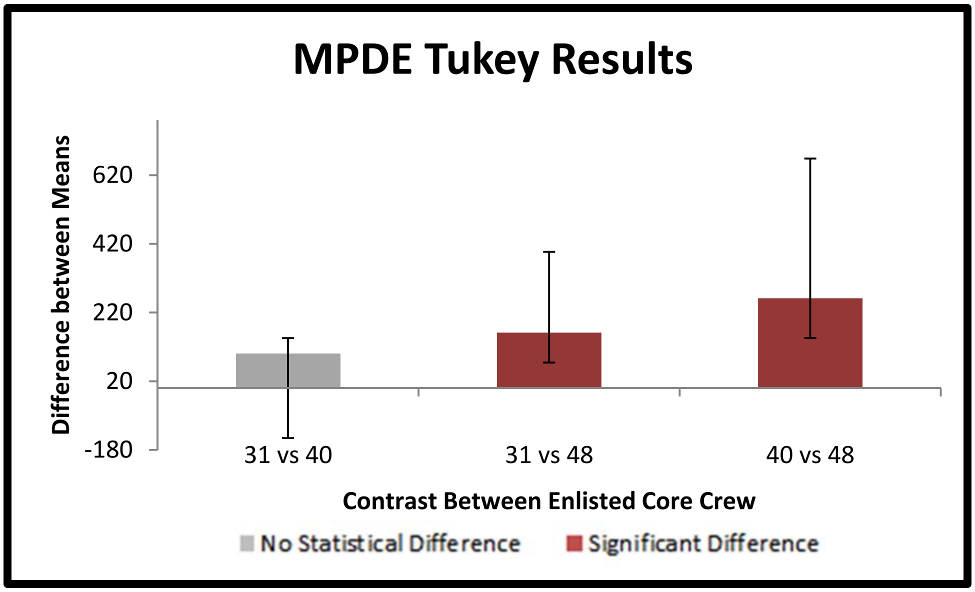


Figure 29. MPDE Tukey results

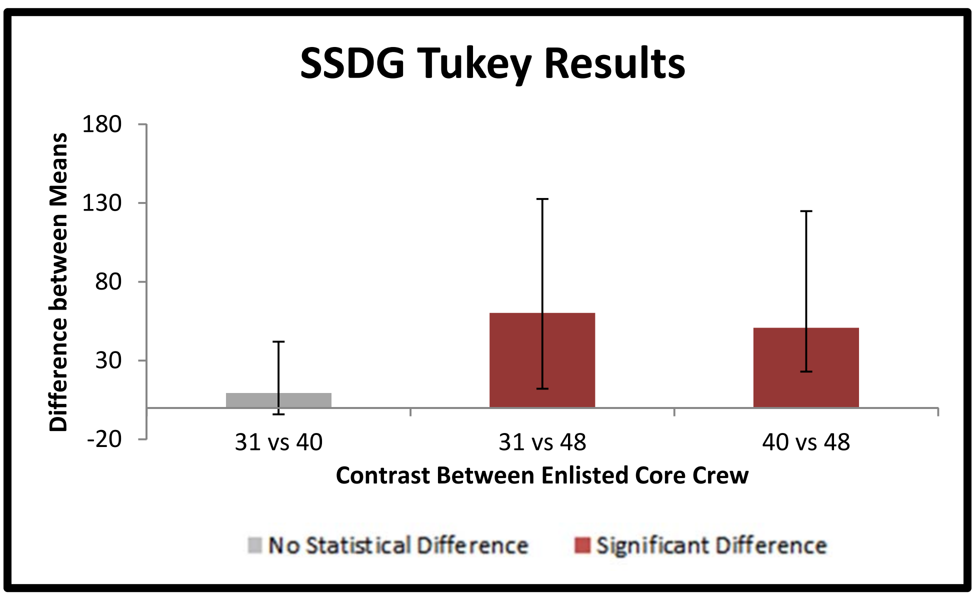


Figure 30. SSDG Tukey results

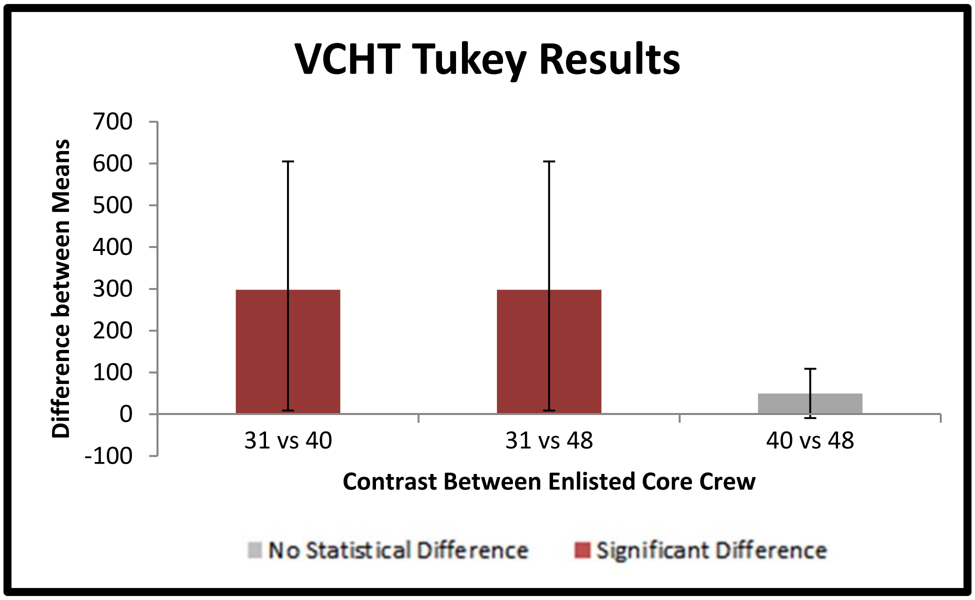


Figure 31. VCHT Tukey results

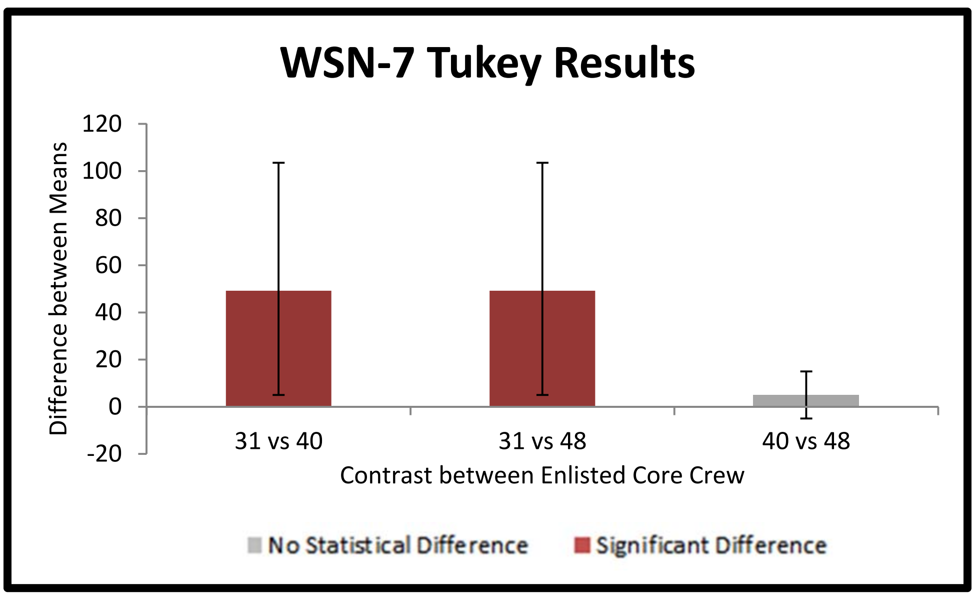


Figure 32. WSN-7 Tukey results

B. FAST RESULTS

FAST was used in this study to predict individual cognitive effectiveness based on sleep and work activity patterns during a 21-day underway for typical watch rotations aboard LCS and to illustrate the most average sleep amount and least average sleep amount found in each of the three IMPRINT models. Figures 33 to 36 display the FAST graphs that illustrate the effects that sleep and watch rotations have on cognitive effectiveness and alertness. No actual sleep data were collected; the work intervals, watch rotations, and sleep epochs used in the FAST models were notional. Because the FAST schedules are notional, however, they represent a "best-case" scenario in which a sailor receives *fair* sleep for the entire 21-days: their sleep is uninterrupted, they are able to fall asleep within fifteen minutes of watch turnover after 1900 and only wake 30 minutes prior to morning watch. FAST was then used to illustrate the sleep and watch schedules from the IMPRINT Pro model simulations and an analysis of variance (ANOVA) test was conducted to determine statistically significant differences in the mean sleep total for each enlisted core crew. The FAST graphs illustrate the IMPRINT, 21-day underway sleep and watch schedule of each sailor. Figures 37 to 42 displays the FAST outputs that illustrate the most average sleep amount and least average sleep amount of an enlisted sailor found in each enlisted core crew model.

1. Predicted Cognitive Effectiveness of a Notional Sailor on a Two-, Three- or Four-Section Watch Rotation

Figure 33 shows the predicted effectiveness of a sailor on a 6/6 watch rotation, standing the same exact watch every day. After only five days, the sailor's predicted effectiveness while on watch is below the 77.5% predicted effectiveness criterion line for the remainder of the time. The sailor's reaction times are comparative to someone intoxicated at a .05 BAC level.

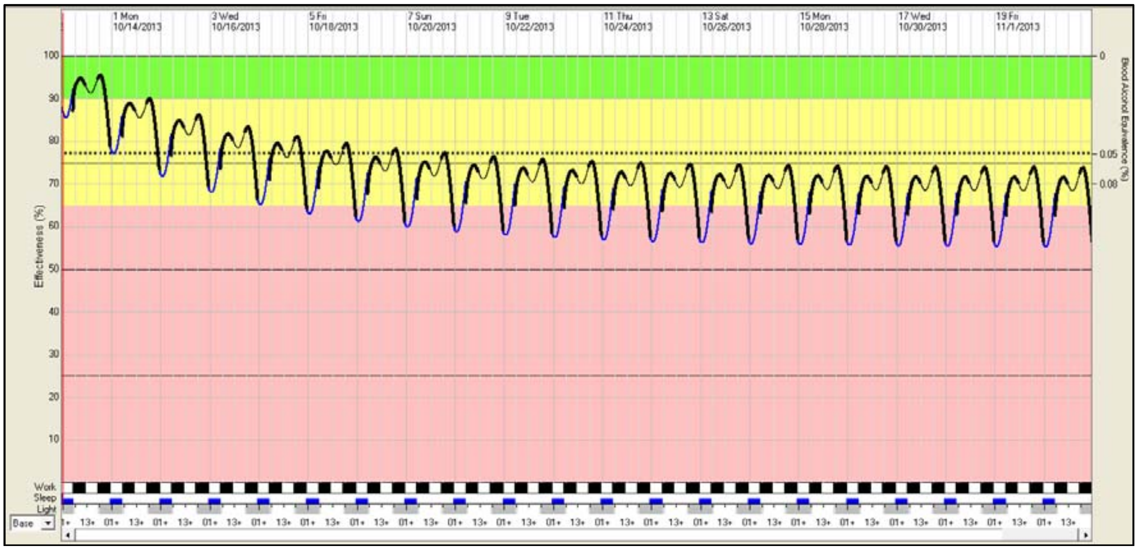


Figure 33. Predicted effectiveness for a sailor on a 6/6 (two-section) watch rotation

Figure 34 shows the predicted effectiveness of a sailor on a 6/6 dogged watch rotation, standing a different watch every day but repeating the rotation every other day. The sailor's predicted effectiveness while on watch falls in the red range below the 65% predicted effectiveness threshold for almost the entire time. FAST shows that the sailor's predicted reaction times are severely impaired—comparable to the performance of an individual intoxicated at a .08 BAC level. It is important to point out that the simulated activities of certain crewmembers of the IMPRINT Model 1 (core crew of 31 enlisted sailors) and Model 2 (core crew of 40 enlisted sailors) were using this same port and starboard (6/6) schedule.

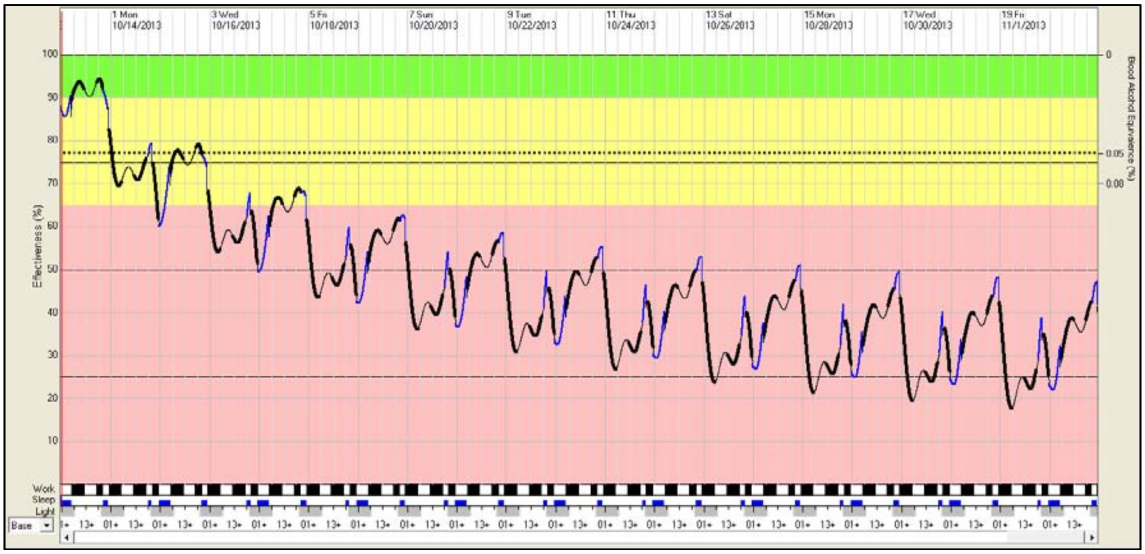


Figure 34. Predicted effectiveness for a sailor on a 6/6 (two-section) dogged watch rotation

Figure 35 shows the predicted effectiveness of a sailor on a 5/10 watch rotation, standing a different watch every day but repeating the rotation every three days. This watch rotation was used in the IMPRINT Pro Forces for enlisted core crew 31 and 40. The sailor's predicted effectiveness while on watch is on the border of the red and yellow ranges below the 77.5% predicted effectiveness criterion line 85% of the time. The sailor's reaction times are predicted to be severely impaired—as if the sailor was intoxicated at a .08 BAC level.

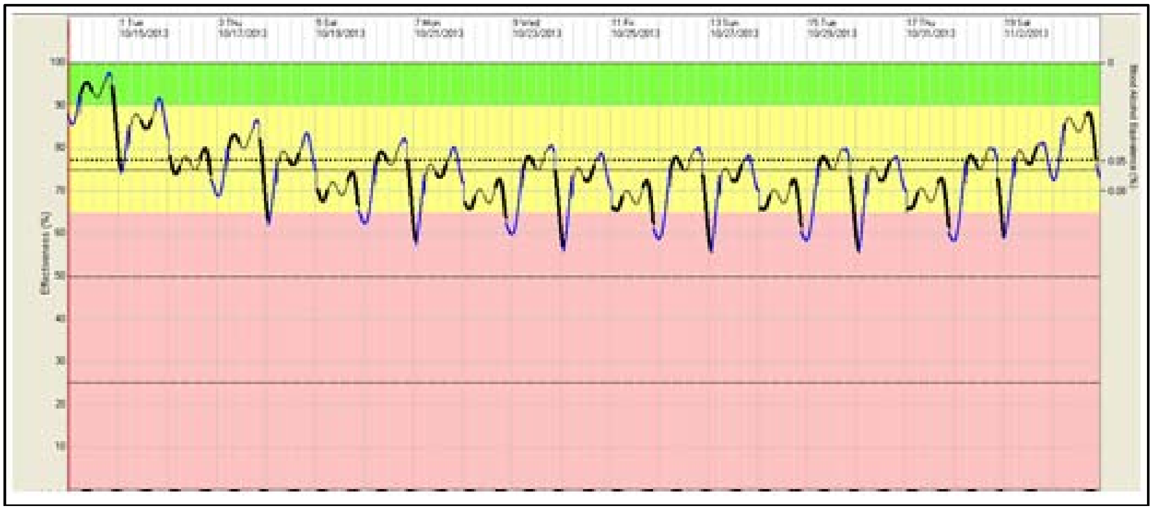


Figure 35. Predicted effectiveness for a sailor on a 5/10 (three-section) watch rotation

Figure 36 shows the predicted effectiveness of a sailor on a 5/15 watch rotation, standing a different watch every day but repeating the schedule every fourth day. The sailor's predicted effectiveness while on watch is in the yellow range above the 77.5% predicted effectiveness criterion line 80% of the time. The sailor's reaction times are higher than the other conditions and the sailor experiences the marginally better predicted effectiveness because their sleep occurs at nearly the same time almost every night. Sleeping at the same time of night is important because doing so increases the chance of maintaining circadian rhythm synchronization.

Figure 36. Predicted effectiveness for a sailor on a 5/15 (four-section) watch rotation

2. Analysis of Most and Least Average Sleep Totals

An analysis of variance (ANOVA) test was conducted to determine statistically significant differences in the mean sleep total for each enlisted core crew. The null hypothesis for this analysis assumed that all the mean sleep totals between enlisted core crews were the same, and the alternative hypothesis assumed that one or more mean sleep totals were different from the others:

$$H_0: \mu 31 = \mu 40 = \mu 48, \text{ all the means are the same}$$

$$H_1: \mu 31 \neq \mu 40 \neq \mu 48, \text{ one or more means are different}$$

The results of the ANOVA test showed no statistical significant difference ($p > .05$) in the mean sleep totals. Therefore, there is not sufficient evidence to reject the null hypothesis. The mean sleep totals may not be significantly different, but the FAST outputs display a different perspective. In Figures 37–42, the predicted effectiveness of the most average sleep totals and the least average sleep totals are displayed for each enlisted core crew. The sleep totals were taken from the activity data report with the same random seed number for each enlisted crew core. FAST can be used as a human performance prediction tool in conjunction with IMPRINT Pro Forces.

Figure 37 shows the predicted effectiveness of the sailor with the most average sleep total for the 31 enlisted core crew (40 core crew). The sailor has a mean effectiveness of 72% while on watch and 46% of the time the sailors predicted effectiveness falls below 70%.

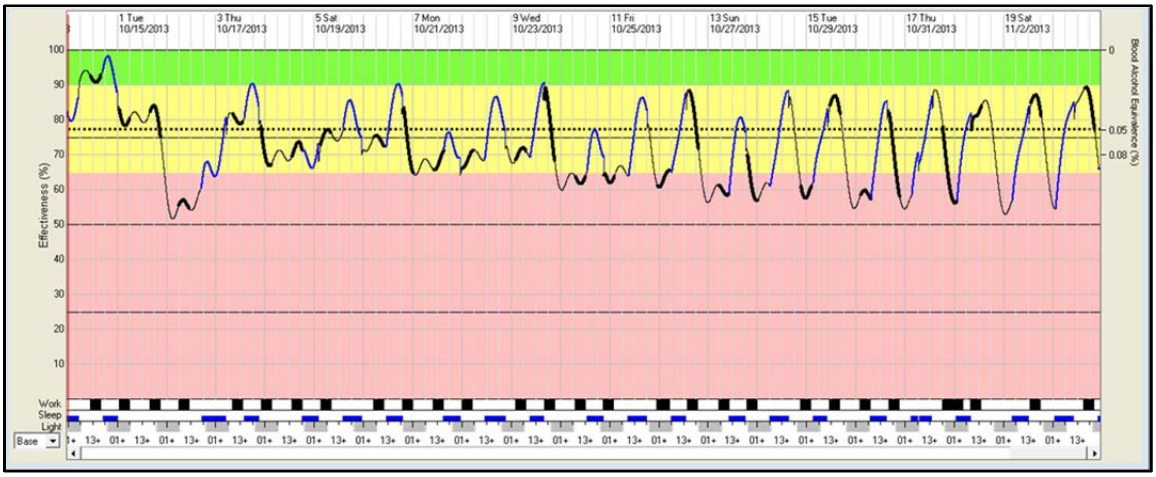


Figure 37. Predicted effectiveness of the sailor with the most average sleep amount from the 31 enlisted core crew

Figure 37 shows the predicted effectiveness of the sailor with the least average sleep total for the 31 enlisted core crew (40 core crew). The sailor has a mean effectiveness of 66.17% while on watch and 78% of the time the sailors predicted effectiveness falls below 70%.

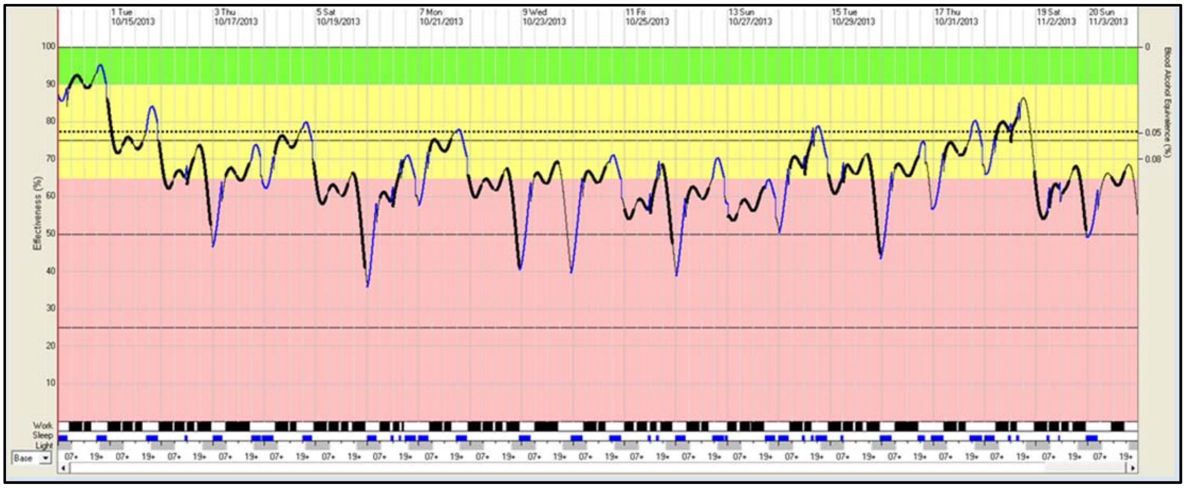


Figure 38. Predicted effectiveness of the sailor with the least average sleep amount from the 31 enlisted core crew

Figure 39 shows the predicted effectiveness of the sailor with the most average sleep total for the 40 enlisted core crew (50 core crew). The sailor has a mean effectiveness of 71.22% while on watch and 41% of the time the sailors predicted effectiveness falls below 70%.

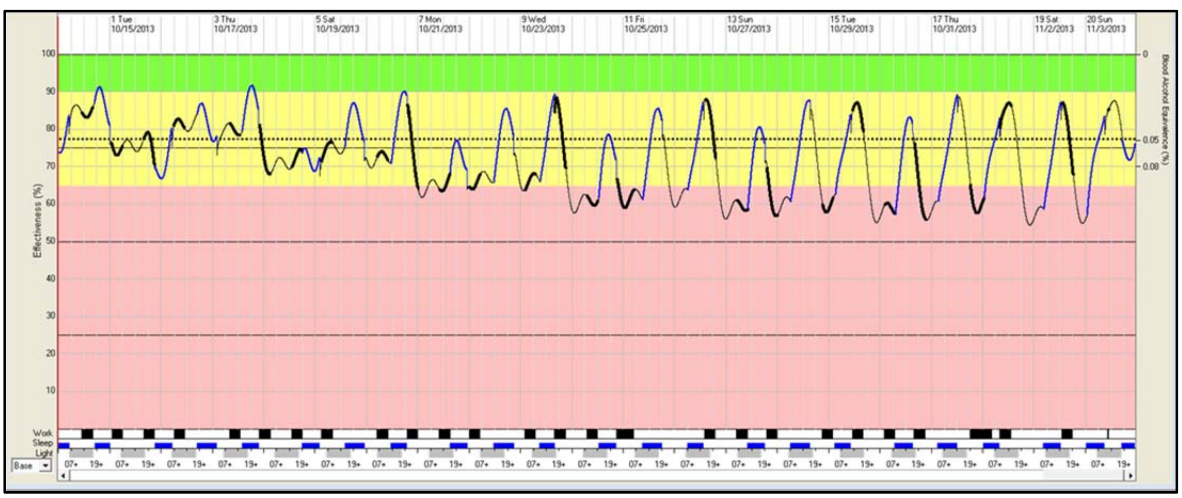


Figure 39. Predicted effectiveness of the sailor with the most average sleep amount from the 40 enlisted core crew

Figure 40 shows the predicted effectiveness of the sailor with the least average sleep total for the 40 enlisted core crew (50 core crew). The sailor has a mean effectiveness of 66.25% while on watch and 64% of the time the sailors predicted effectiveness falls below 70%.

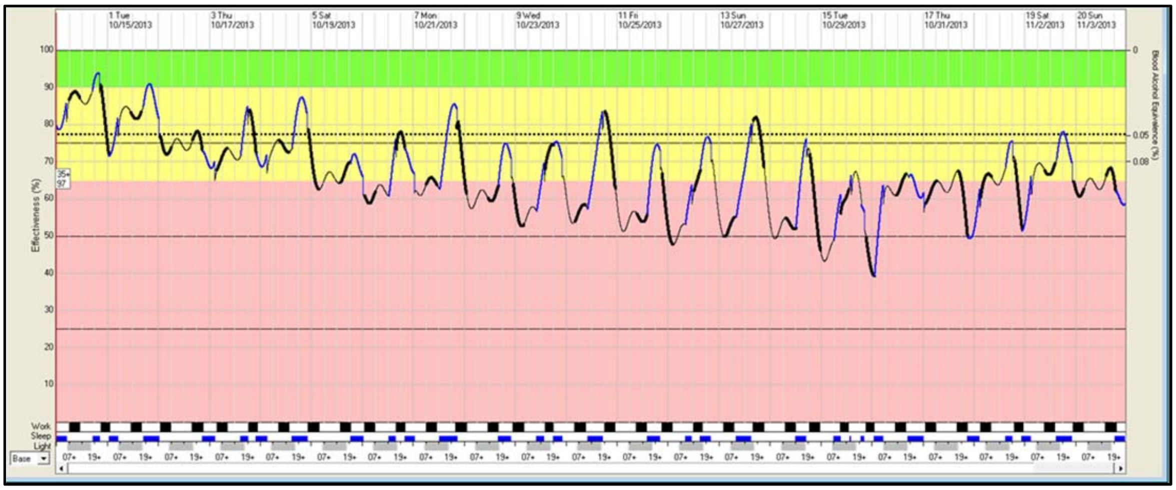


Figure 40. Predicted effectiveness of the sailor with the least average sleep amount from the 40 enlisted core crew

Figure 41 shows the predicted effectiveness of the sailor with the most average sleep total for the 48 enlisted core crew (60 core crew). The sailor has a mean effectiveness of 81% while on watch and the sailors predicted effectiveness never falls below 70%.

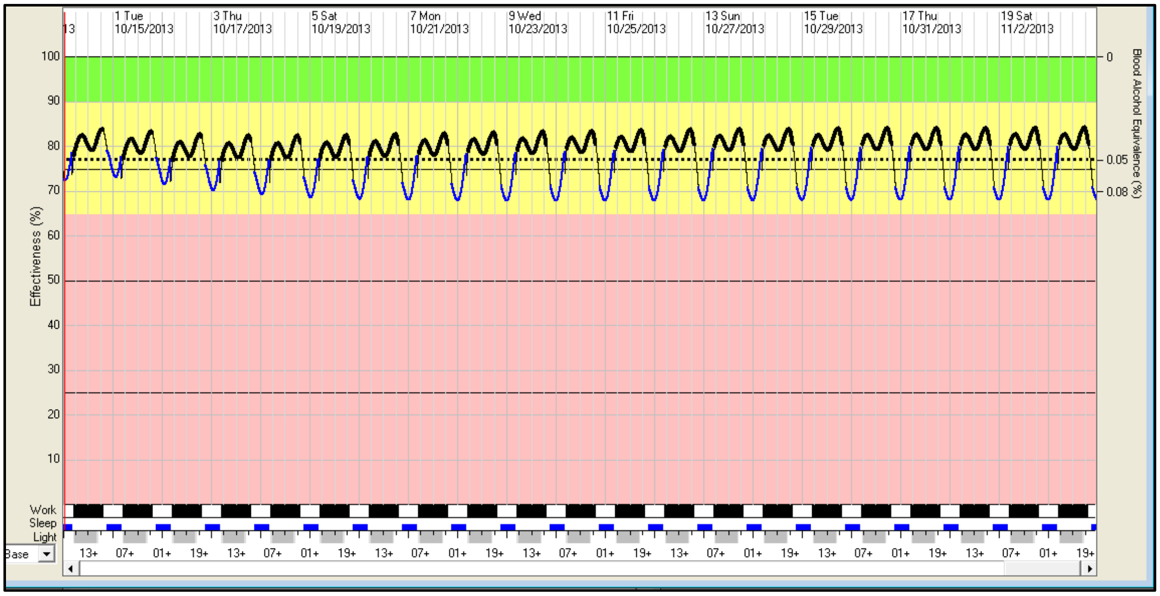


Figure 41. Predicted effectiveness of the sailor with the most average sleep amount from the 48 enlisted core crew

Figure 42 shows the predicted effectiveness of the sailor with the least average sleep total for the 48 enlisted core crew (60 core crew). The sailor has a mean effectiveness of 74.93% while on watch and 19% of the time the sailors predicted effectiveness falls below 70%.

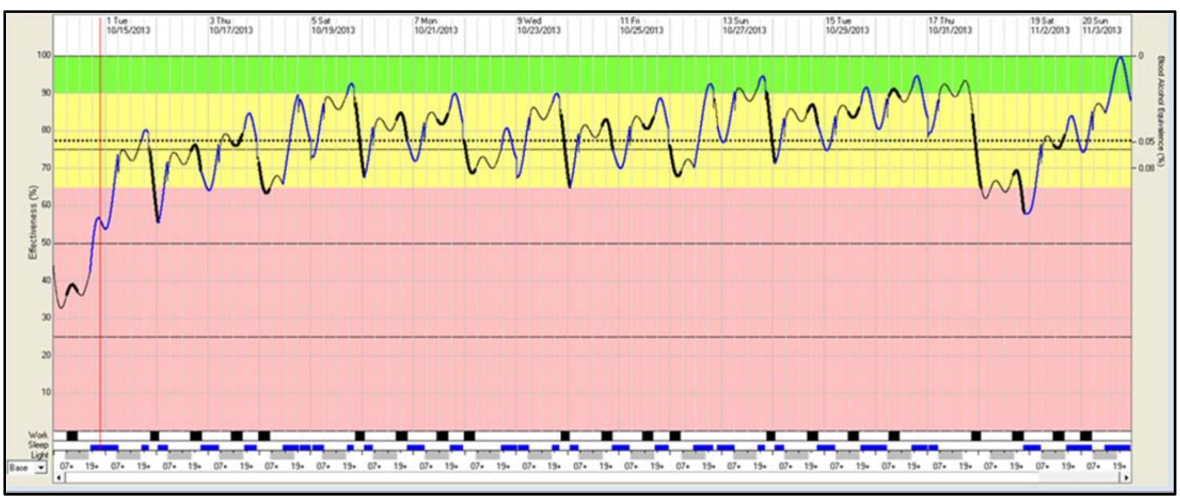


Figure 42. Predicted effectiveness of the sailor with the least average sleep amount from the 48 enlisted core crew

C. LCS SURVEY

A survey was developed and administered to crew 202/GOLD aboard the USS *Independence* (LCS 2) in January of 2014. A total of 33 sailors completed a baseline survey to collect data on certain attributes of the LCS crew and their work patterns during an operational underway. The survey was administered to solicit personal opinions on the current watch rotations, the workload of departments and positions, and the amount of sleep the current watch rotation allows. Question one asked what watch rotation they were currently working. Of the 33 sailors (officers and enlisted), 27 actually stood watch. Forty-five percent of the 27 LCS 2 sailors were on 5/10 (three-section) watch rotation, as shown in Figure 43.

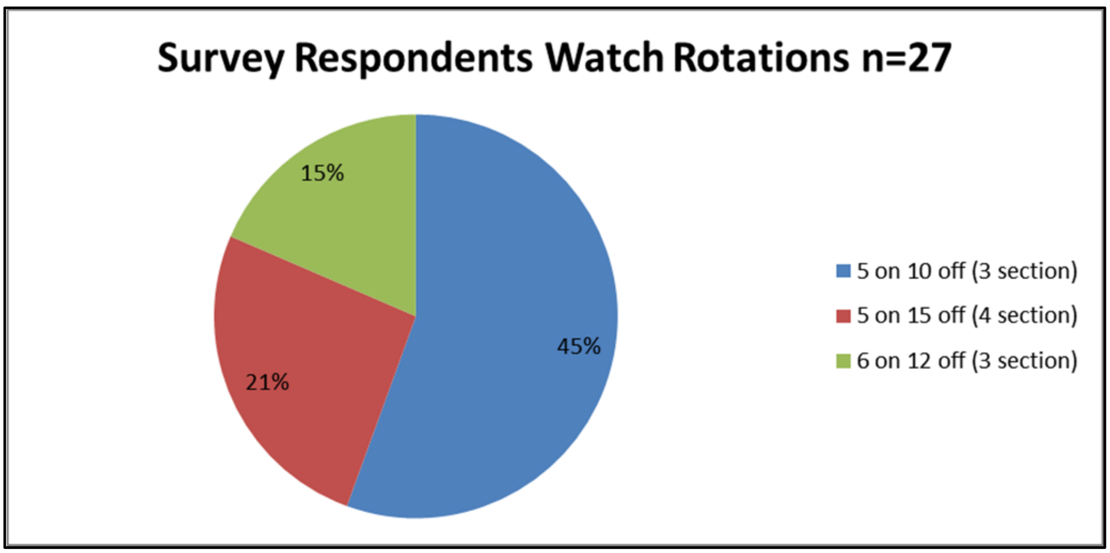


Figure 43. Watch rotations of survey respondents

The next couple of questions asked which departments they thought had the highest workload and which had the lowest workload. All 33 participants responded that they thought engineering department had the highest workload and operations department had the lowest. This corresponds directly to the IMPRINT Pro Forces output reports. Engineering department had a lot of unplanned events fail between the enlisted core crews while operations department had zero. This means that, in the IMPRINT Pro Forces module, operations department had sufficient personnel to complete their daily planned activities and successfully complete all unplanned events for all three core-crew sizes. Engineering department's initial manpower deficiency led to many unsuccessful unplanned events, but later thrived when additional personnel were added, as shown by IMPRINT Pro Forces unplanned event status reports.

V. CONCLUSIONS

This thesis was a case study used to validate using government-developed, human performance software to assist in fleet manpower determination. The IMPRINT Pro Forces module was used to simulate three LCS enlisted core crew sizes (31, 40, and 48) and to estimate the capability of each to respond to daily planned activities and unplanned events during a typical underway period. In short, we wanted to analyze IMPRINT Pro Forces' capability to determine a core crew size that can adequately operate an LCS ship. Comparisons between the models show statistically significant differences in the number of unplanned event failures, as proven by the ANOVA and Tukey HSD tests. In other words, IMPRINT Pro Forces was able to show that as core crew size increased, system performance improved (as evidenced by decreasing failure rates with increasing crew size). The enlisted core crew of 40 consistently outperformed the enlisted core crew of 31, and the enlisted core crew of 48 significantly outperformed both 31 and 40. Additional work should be done to refine the baseline settings and underlying model assumptions for various platforms. IMPRINT Pro Forces is certainly a valuable tool that expands the current manpower requirements determinations capabilities.

FAST provided another important method to analyze the performance of individual sailors as core crew size increases or decreases. We used the sleep and watch times from IMPRINT Pro Forces reports in order to model a sailor's 21-day, IMPRINT schedule. The FAST illustrations showed the percentage of time the sailor was under a 70% effectiveness level on watch. As the core crew size increased, the percentage of time a sailor spend under the 70% effectiveness level decreased by a sizeable amount. The FAST results showed that LCS core crew size, according to IMPRINT Pro Forces, has a significant effect on sailor performance.

The LCS 2 survey was used to validate IMPRINT and FAST results. Every survey respondent stated that engineering department had the highest workload and that operations department had the least. The IMPRINT results for the enlisted core crew of 31 (40 core crew) showed that engineering department had the highest equipment failures due a manpower deficiency. When asked what manpower changes should be made to improve the performance of LCS, the majority of LCS 2 survey respondents stated more sailors were needed. (Many stated one or two sailors should be added to each department.) The IMPRINT Pro Forces and FAST results showed significant performance improvement when changing from a core crew of 31 to a core crew of 40, and a profound improvement with a core crew of 50.

By analyzing the results of the three IMPRINT Pro Forces models together with the FAST illustrations and the LCS 2 survey results, we conclude that the IMPRINT Pro Forces module produces significant and valuable results that can help inform leaders on proper crew sizes for LCS. When supplemented with FAST, IMPRINT Pro Forces results are even more complete and can highlight individual human performance effectiveness. These human performance analysis tools can and should be used by the U.S. Navy for ship manpower determination. IMPRINT Pro Forces and FAST can help prevent ship manpower overestimation or underestimation and can shorten, or even prevent, misalignment of scarce human resources, and/or crew fatigue and improve the precision of manpower requirements determinations for new acquisitions and existing platforms.

VI. RECOMMENDATIONS

A. U.S. NAVY

When a system operates or is designed to operate with minimal manpower and reduced redundancy, caution must be paid to the limitations of the human in the system. Senior leaders in the Navy should be aware of the sophisticated human performance analysis models and tools currently available for manpower determination. IMPRINT Pro Forces and FAST have been shown in this case study to more accurately estimate workload and human capabilities and can be used to supplement the current NSWW calculations.

Simple policy standards, like watch-rotation capability, can have a large effect on crew performance. Watch rotations must be given careful attention as a policy, especially when allocating manpower to systems that operate with minimal manning. Watch rotations alone can have a damaging effect on a crew's cognitive performance, thus impacting combat effectiveness in a negative way. Understanding how a four-section watch rotation will affect a crew verses a crew that is only able to operate a two or three-section watch has a significant impact on performance over a 2-week period, as shown in the FAST outputs for watch rotations in Chapter IV Results. Crew size also will impact sailor performance as shown in the IMPRINT Pro FAST schedules. As crew size decreases, sailors' endurance is stretched thin because of human fatigue, and increased cognitive load. When crews are not sized adequately, workload can become overwhelming and impossible to accomplish within acceptable fatigue levels. Thus, an environment is created that is unsafe, unsustainable, and detrimental to crew and material readiness.

As shown in this case study, the DoD has developed and now owns sophisticated software that can measure workload and human capabilities within a system. The Navy should be aware that different situations require different policy standards. NAVMAC should supplement their workload analysis and manpower determination metrics with IMPRINT Pro Forces and FAST, in conjunction with updates to the NSWW to more accurately depict actual sailor workload. Accurately determining manpower requirements under situations like minimal manning or specially designed system requirements is possible with human performance software.

B. FUTURE WORK

A Navy-centric database for IMPRINT Pro Forces module should be developed. Such a database would significantly improve the flexibility of analysts and provide ad-hoc query capabilities across multiple platforms. The additional modifications to the underlying assumption will also improve the accuracy and details of the results allowing for deeper analysis. The IMPRINT Pro Forces module can be used to run simulations for other units including other surface platforms, shore commands, and squadrons if specific databases for these systems were created and updated (i.e., with Navy personnel rates, maintenance standards, and equipment). Evaluating other units further tests the capability of IMPRINT Pro Forces to accurately evaluate changing manpower levels.

This case study was narrow in its scope and only analyzed the enlisted crew of the LCS1 platform. The results are not a complete representation of the entire fleet or the rest of the LCS fleet for that matter. It is recommended that IMPRINT Pro Forces be used to model an entire LCS crew including officers, and also take in effect that corrosion control and corrective maintenance are unplanned events as well.

Further research should expand on the use of IMPRINT Pro Forces reports using FAST. Future studies should model the best and least average sleep totals, but should find the best and worst of the 100 runs. Paired comparisons can be performed within and across various crew sizes. The results will show a more accurate range of average LCS core crew sleep amounts over a period of time.

Another study could run the IMPRINT Pro Forces Module with more innovation watch bills like the 3/9, and then compare those with commonly used watch bills. The purpose of this study would be to analyze how the change in watch bills affects the crew performance in IMPRINT Pro Forces. The final step of the study would be to input the IMPRINT sleep and work results into FAST, and compare performance.

APPENDIX. SURVEY QUESTIONS

RATE__________ CORE CREW? YES/NO

1. What is your current watch rotation?

2. What departments onboard LCS 2 do you think have the highest workload?

   1.___________________
   2.___________________
   3.___________________

3. What departments onboard LCS 2 do you think have the lowest workload?

   1.___________________
   2.___________________
   3.___________________

4. The current watch rotation allows for ______________ rest than needed. (Circle one)

   - Much Less
   - Less
   - About Right
   - More
   - Much more

5. What manpower changes would you make to improve the effectiveness of LCS?

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